

FINAL REPORT

Munition Mobility in Mixed Grain (Sand, Gravel, Cobble) Environments

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Executive Summary:
SERDP Project Number MR21-1333
Munition Mobility in Mixed Grain
(Sand and Cobble) Environments
Meagan Wengrove and Gabriel García Medina

The primary objective of the proposed work was to classify and compare the vulnerability of munition migration, exposure, and burial between 100% pure homogeneous beaches (sand or cobble) to two mixed grain beach compositions with varying sand to cobble ratios. Within this goal were three sub-objectives:

- Test munition mobility, exposure, and burial response to swash bore impact on laboratory scale mixed grain beach compositions (30% cobble and 50% cobble) and compare results to purely sand and cobble experiments.
- Test three surrogate types similar in shape, density, diameter, and length to those residing in the nearshore munition contaminated FUD environments.
- For each beach composition and munition type, experimentally and numerically determine the influence of beach state (mild, intermediate, and steep) on swash velocities and corresponding impact to munition mobility.

To achieve these goals a double-dambreak flume experiment was conducted on a laboratory beach with slope of 1:7. The investigation and analysis of munition mobility in this study span a range of beach compositions from purely homogeneous (sand or cobble), to mixed grain beach compositions of varying sand/cobble ratios (70% sand / 30% cobble or 50% sand / 50% cobble). Three surrogate munition types (M20, M40, and M40R2) of variable densities (7999 kg/m^3 , 5720 kg/m^3 , and 2460 kg/m^3) and diameters (2 cm, 4 cm, and 9 cm) were tested under repeated single swash forcing conditions conducted in a double-dambreak wave flume at the University of Delaware. Two munitions of the same type (size and density) were initially deployed at a downslope ($X = 1.5 \text{ m}$) and upslope ($X = 2.5 \text{ m}$) beach location to assess munition mobility at variable swash energies and water depths. Water depths, beach profile, horizontal runup extent, instantaneous bore front velocities, and intrabore near-bed flow velocities were measured. To supplement these measurements, several numerical experiments based on a non-hydrostatic phase resolving model were simulated. The sediment transport regimes of the four beach compositions are analyzed. Maximum object mobility numbers achieved during the laboratory double-dambreak flume experiment are compared with observed critical object mobility numbers and the numerical simulation results.

The main conclusions are summarized as follows. Depending on the beach composition and munition initial deployment location, the dam-break generated swash would generally initiate motion on the backwash of the bore. Backwash induced incipient motion was observed for 11 different munitions during initial swash events (Trial 1) on the 30% cobble and 50% cobble beach compositions. Only the least dense and largest munitions reached incipient motion during the bore uprush impact. In addition to the swash hydrodynamics, the size and density of the munitions relative

to the beach bed roughness have been shown to play a significant role in whether a munition would mobilize downslope or bury. As the density of the munitions increased, total downslope munition migration decreased. Interestingly, the response of the beach profile and overall munition mobility on the 50% cobble beach was nearly the same behavior observed for the 30% cobble beach with net-offshore directed sediment transport and offshore munition migration. However, the mixed grain beach morphology and munition behavior were much different than the pure sand and cobble beach behaviors. For the pure sand, 30% cobble and 50% cobble beach compositions, the least dense munitions (M40R2) were observed to move and follow the direction of the runup, but during all events resulted in net-offshore directed migration. Munition migration distances for all munition types on the pure sand and mixed grain beach compositions generally increased as the percentage of sand in the mixture increased, implying the roughness of the beach is potentially a controlling factor for beach development and object mobility.

Swash bore velocities developed on the 100% cobble beach were not significant enough to induce munition mobility during uprush or backwash for any of the munition types nor at either of the initial deployment locations. Instead, all munitions on the cobble beach were observed to be covered by rolling cobbles. Specifically, the M20 munitions at both locations were completely covered after five consecutive swash events due to morphological burial of net-onshore directed sediment transport of the cobble beach during uprush. The beach profiles and munition mobility on the pure cobble beach were subject to greater infiltration of water even though they initially were forced with the same initial swash conditions as the pure sand and mixed grain beach compositions.

Laboratory results guided NHWAVE numerical experiments to determine the influence of beach state (intermediate, steep) on swash bore acceleration and corresponding impact to munition mobility. We saw that the bore shape and forcing was highly influenced by beach slope, which could in and of itself influence munition mobility. A combination of model results and munition mobility number can be used to guide scenarios where munitions are expected to move.

The object mobility number, akin to the Shields parameter, is used to predict munition motion and is presently a function of water velocity and munition density. Extracted local intra-bore near-bed backwash velocities and water depth at the instant of migration (roll) are used to calculate critical object mobility numbers. Object mobility numbers increased as munition density decreased and were the largest on the 50% cobble beach. Maximum slope correct object mobility numbers for each munition type and beach composition were calculated. Comparison between maximum bore velocities and bore velocities at the time of munition motion imply that water velocities did not have to reach the maximum observed for munitions to migrate on the sandy beach mixtures. With our laboratory and numerical model observations, we suggest that the accuracy in the object mobility number would benefit by including a friction term that accounts bed roughness, a bed slope modification for both uprush and downrush, and a bed infiltration/liquefaction modification to account for sediments that are more or less porous.

We suggest future work to 1) improve the object mobility number, 2) test different sediment composition that are more heterogeneous than the bimodal distribution tested in these experiments, 3) test mobility in different parts of the surf/swash/river zone where heterogeneous sediments exist, 4) explore the effects of beach heterogeneity on munition mobility and burial variability.

Final Report: SERDP Project Number MR21-1333 Munition Mobility in Mixed Grain (Sand and Cobble) Environments

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Abstract

Nearly 24% of Formerly Used Defense Sites (FUDS) containing military munitions are in the nearshore coastal zone with approximately 30% of those sites containing heterogeneous sediment compositions of gravel/cobble and sand. Previous exploration in munition mobility was performed on beaches of sandy or muddy bottoms leaving the influence of heterogeneous sediment properties on coastal processes and munition mobility unstudied. The primary objective of this study is to classify the vulnerability of munition migration, exposure, and burial on mixed grain beaches within the swash zone. Double-dambreak flume experiments were performed on four permeable beach compositions consisting of pure sand, pure cobble, 30% cobble- and 50% cobble- to sand ratios. Beach slope was initially set to a 1:7 slope. For each sediment composition, three munition types, varying in size and density, were explored at two different energetic beach locations. Munition mobility was measured manually and tracked during the swash event, along with the beach hydrodynamics such as runup extent, flow velocities, water depth, internal sediment pore pressure, and beach profile morphological development. Net munition migration distances were the least on the pure cobble beach and the greatest on the pure sand each compositions, with the mixed grain beaches modifying munition mobility (Figure 21), likely due to bed friction. Incipient motion and migration for the least dense munition was the soonest and largest for all beach compositions, respectively (Figure 21); and for the two-densest munition types motion occurred during backwash only. Minimal correlation between the

present formulation of the object mobility number and total distance traveled by the munition were observed (Figure 28). We hypothesize that the object mobility number should be modified for slope, friction, and infiltration characteristics of the beach profile to better mimic observations of munition mobility on mixed grain beaches. Lastly, laboratory results guided NHWAVE numerical experiments to determine the influence of beach state (intermediate, steep) on swash bore acceleration and corresponding impact to munition mobility and are used to predict munition mobility on 30% cobble and 50% cobble beach compositions (Figure 24, 30). Finally, we suggest future goals for this line of work at the end of the report.

Contents

1	Contact Information	7
2	Introduction	8
2.1	Swash Zone Dynamics	8
2.1.1	Runup on varying slopes	9
2.1.2	Swash dynamics & runup on cobble beaches	10
2.2	SERDP and the Munition Response Program	12
2.2.1	Munition mobility in the sandy shoaling, breaker, and surf zones	14
2.2.2	Munition mobility in the sandy swash zone	15
2.2.3	Object mobility and variability by size, shape, and density	16
2.2.4	Munition Mobility Related to Mixed Grain Beaches	17
3	Methods	21
3.1	Dambreak Swash & Experimental Design	21
3.2	Beach Compositions	23
3.3	Surrogate Munitions	26
3.4	Experimental Configurations	27
3.5	Instrumentation & Signal Processing	29
3.5.1	Hydrodynamic measurements	29
3.5.2	LiDAR	35
3.6	NHWAVE Numerical Experiments	41
4	Results	43
4.1	Hydrodynamic Observations	43
4.1.1	Measurements of water surface elevation & water depth	43
4.1.2	Water Velocities	51
4.1.3	Pore Pressure Gradients	54
4.2	Morphology Observations	55
4.2.1	Beach development	57
4.3	Observations of sUXO Mobilization	58
4.3.1	Mobility during a single swash event	58
4.3.2	Mobility during consecutive swash events	61
4.4	NHWAVE Hydrodynamic Results	64

4.4.1	Dambreak Swash Vulnerability to Changes in Slope & Initial Bore Energy	65
5	Discussion	70
5.1	Hydrodynamic and Morphodynamic Response	70
5.2	sUXO Response.....	73
5.2.1	Slope corrected object mobility number	75
5.2.2	Overall Munition Mobility	75
5.2.3	Munition Incipient Motion.....	77
6	Conclusion	83
7	Future work	85
A	Appendix: List of Acronyms	93
B	Appendix: CACR Flume Sensor Schedule	94
C	Appendix: Velodyne LiDAR Post-Processing for Hydrodynamic Analysis	95
D	Appendix: Lidar “Noise Floor”, Range, and Minimum Water Level Criteria	100
E	Appendix: Reflectivity Investigation for capturing runup	102
F	Appendix: Unique Series Munition Measurements	103

List of Figures

1	Munition Response project locations	12
2	WWII munition remnants.....	18
3	UD CACR Double-Dambreak Small-Scale Wave Flume	23
4	Experimental beach compositions.....	25
5	Surrogate munitions	27
6	Hydrodynamic station cart layout.....	31
7	Beach creation process	33
8	Druck pressure sensor processing scheme	35
9	Velodyne mounting orientation.....	36

10	RealSense camera mounting	39
11	Schematic of UD CACR Small-Scale Wave Flume sensor layout	40
12	NHWAVE dambreak simulation.....	42
13	Separated Water and Bed Measurements	44
14	Water depth at munition initial deployment locations.....	46
15	Runup extent for all four beaches	49
16	Velodyne extracted horizontal runup and velocity measurements	51
17	Intrabore near-bed water velocities	53
18	Internal pore pressure gradients	54
19	Trial 1 vs Trial 5 beach profile differences	56
20	Trial 1 munition trajectory comparison	60
21	Munition horizontal migration	63
22	NHWAVE calibration process	65
23	Comparison of laboratory observations and NHWAVE numerical simulations	67
24	NHWAVE modeled water velocities vs water depth for simulations of altered slope and varied initial bore energy	69
25	Slope corrected maximum object mobility number vs observed series-averaged horizontal displacement of the munition.....	77
26	Slope corrected critical object mobility number vs intrabore near-bed velocities for each beach composition	79
27	Threshold for initiation of munition motion.....	81
28	Pre-stationary scan of the pure sand beach leveled to the initial 1:7 slope.	97
29	Bathymetric Interpolation scheme comparison for the sand beach	98
30	Velodyne noise floor exploration	101
31	Using LiDAR intensity to extract runup extents.	102
32	Munition migration measurements for Sand: $X = 1.5$ m.....	103
33	Munition migration measurements for Sand: $X = 2.5$ m.....	103
34	Munition migration measurements for Cobble: $X = 1.5$ m.....	104
35	Munition migration measurements for Cobble: $X = 2.5$ m.....	104
36	Munition migration measurements for 30% Cobble: $X = 1.5$ m	105
37	Munition migration measurements for 30% Cobble: $X = 2.5$ m	105
38	Munition migration measurements for 50% Cobble: $X = 1.5$ m	106
39	Munition migration measurements for 50% Cobble: $X = 2.5$ m	106

List of Tables

1	sUXO Attribute Table	26
2	Experimental Configurations	29
3	Number of trials used for horizontal runup estimates by beach composition	44
4	Schedule for Cart Station Sensors (H#) and Buried (B#) Sen- sors	94

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2 Introduction

Underwater munitions are exposed to harsh environmental conditions due to waves, currents, tides, storm induced surge, and morphological change that results in a range of munition mobility and burial patterns. Munitions that were once offshore, can be transported to within the swash zone (MacDonald et al., 2004) and become a serious threat to the environment and public health. The probability of munition mobilization in the underwater environment depends heavily on the munition type (i.e. size, diameter, shape, and density), the combined wave and current forcing conditions, and sediment type. Predicting munition behavior relies on understanding the hydrodynamic, and morphological conditions unique to each underwater region and is critical for future response planning and remediation efforts (SERDP, 2018). Motivated by the need to enhance the predictability of munition behavior in the nearshore region, the hydrodynamics of wave bore runup on varying slopes and beach compositions is first introduced for sand, cobble, and mixed grain beach compositions. Previous investigations and observations of munition mobility in different underwater conditions is considered next, but reveals how the influence of non-homogeneous beach compositions on munition migration and burial for variable munition densities and shapes have yet to be quantified, nor observed. Thus, this study focuses on swash zone dynamics and runup on varying slopes with respect to munition mobility and burial patterns of variable munition types and beach compositions.

2.1 Swash Zone Dynamics

Within the nearshore are three main breaker types: spilling, plunging, and surging. The type of breaker is often determined by the relative bottom slope at time of breaking, the wave period, and the equivalent deep water steepness (H_0/L_0) (Svendsen, 2006). Independent of type, the collapsing water creates a turbulent and air-entrained roller that continues to ride the front of the wave. This is also known as a bore or moving hydraulic jump. The bore will eventually collide with the shoreline to form the swash zone. The swash zone is therefore a highly dynamic region where the waves and coastal processes from the inner surf zone interact with the land via cyclical waves washing up and running down the beach foreshore (Chardón-Maldonado et al., 2016; Koudstaal, 2016). As such, the foreshore lies between the inner surf zone and

back beach and is intermittently submerged and exposed by a relatively thin layer of water (Luccio et al., 1998). The maximum horizontal extent of the waves washing up the foreshore region is known as the runup extent and is heavily influenced by rapid and unsteady flows, high turbulence levels, low and high frequency swash periods, large sediment transport rates, and rapid morphological change (Masselink and Puleo, 2006; Puleo and Holland, 2001). The beach state, or slope, will effect the swash hydrodynamics and influence maximum runup extent as well. In general, low sloping beaches have dissipative properties to which runup amplitude is dominated by low frequency swash periods (characteristic of group waves) breaking on the beach. Group waves are described as a train of at least two waves, traveling in the same direction towards the shore, at slightly different wave periods, but having equivalent wave heights. The resulting amplitude of the combined waves will be superimposed, and wave velocities (celerity) combined (group celerity). The movement of energy generated by a train of waves tends to be slower than that of the individual waves, which in turn can generate the lower frequency swash motions up and down the beach. Conversely, steeper slopes can be highly reflective and are typically dominated by high frequency swash periods generated by individual waves breaking on the beach. Nonetheless, dissipative, reflective, and intermediate beaches can all experience both high and low frequency swash making it challenging to predict the typical beach behavior, swash hydrodynamics, and maximum runup extent based on beach state alone.

2.1.1 Runup on varying slopes

The beach foreshore is the sloping section of the beach profile extending offshore from the berm to the low tide mark. The time series evolution of horizontal runup extent along the beach foreshore at specific cross-shore locations are noticeably asymmetric. The asymmetry is due to the influx of momentum of additional fluid into the back of the bore (Baldock et al., 2014) and is caused by a rapid increase in water depths during uprush that decrease at a slower rate after flow reversal. The acuteness of this asymmetry is dependent on both beach state and location in the cross-shore, with more asymmetric waves on steeper beach slopes characteristic of larger grain sediment (Guard and Baldock, 2007) and symmetric in shape on shallower beach slopes composed of fine, unimodal sediment. However, intermediate beach slopes constantly change from dissipative to reflective states. This implies

that for equal horizontal runup extent, there are many solutions that will result in fast velocities for steep beaches, slow but prolonged velocities for mildly sloping beaches, and a combination of both for intermediate beaches. Typical uprush (and backwash) velocities range from 1.5-3 m/s (and 1.0-2.2 m/s) on a sandy beach (Chardón-Maldonado et al., 2016). In addition, surf-zone controls such as sandbars (Cohn and Ruggiero, 2016) and abrupt slope changes (García-Medina et al., 2020) can significantly alter swash characteristics for the same incident wave sequence. The destabilizing energy from bore driven uprush and backwash interactions, turbulence, and bed shear stresses are shown to lead to large sediment transport gradients (Chardón-Maldonado et al., 2016). Gradients in the sediment transport rate induce accretion or erosion of the beach face. The hydrodynamics within the swash zone on various beach compositions (predominately on pure sand beaches) have been extensively studied, however, the links to sediment transport and resulting hydrodynamic process and morphology prediction are still not well understood (Elko et al., 2015).

2.1.2 Swash dynamics & runup on cobble beaches

In many cases, the morphological and hydrodynamic evolution of a beach is fundamentally related to the beach slope, sediment grain size, bed roughness, porosity, and infiltration rates experienced on the foreshore region during each swash event. The most common type of mildly sloping beaches are comprised of pure sand compositions whereas steeper gradient beaches are dominated by much larger grain size distributions like gravel. The Wentworth (1922) grain size classification scheme defines gravel as being large, coarse grained sediment with a d_{50} size range between 2 mm and 256 mm. As such, it is used to describe three subsets of large sediments, cobble ($64 \text{ mm} < D_{50} < 256 \text{ mm}$), pebbles ($4 \text{ mm} < D_{50} < 64 \text{ mm}$) and granules ($2 \text{ mm} < D_{50} < 4 \text{ mm}$). For practical purposes, three types of cobble beaches have been classified: (1) a pure cobble beach, classified as being dominated by cobble throughout the vertical and horizontal profile regimes; (2) a mixed sand and cobble beach which is homogeneously comprised of sand and cobble; and (3) a composite cobble beach that consists of a steep upper foreshore dominated by cobble and a lower-gradient sandy slope seaward of the cobble face (Coates and Daamgard, 1998; Jennings and Shulmeister, 2002). The uprush and backwash over a purely cobble beach are described similarly to those of a sand beach such that the runup and water depths on non-homogeneous beach

compositions are asymmetric and the momentum of the fluid during uprush is transmitted to the cobble and can induce motion. For highly reflective beach states, the asymmetry of the runup is observed to increase, and is largely a result of the porosity of the sediment. Once the bore front reverses direction, water depths are shallower due to infiltration on the receiving end of uprush, and backwash velocities are controlled by gravity and appear less energetic (Luccio et al., 1998). The steep reflective profiles and morphological features of pure cobble beaches such as ridges, berms, steps and cusps, and the lack of nearshore bars also promote large collapsing/plunging waves capable of mobilizing large amounts of cobble during each event (Austin and Masselink, 2006; Austin and Buscombe, 2008; Masselink et al., 2010). However, significant morphological change and sediment transport on a pure cobble beach has been observed as being asymmetric with signs of accretion and erosion dominating the change in beach morphology (Almeida et al., 2015).

Mixed sand and cobble beach compositions are the most unstable form of the three cobble beach types in that the mixture of sediment grain size can create a range of intermediate beach states that constantly change from being reflective or dissipative depending on the offshore wave characteristics, currents, and tidal regimes. The intermediate beach state is largely due to the uniform grain size distribution that causes the smaller sediments to fill the void space in the beach. While this lowers the porosity of the beach, the swash asymmetry is reduced and changes the reflective properties of the beach (Blenkinsopp et al., 2022). However, the combined low porosity and steeper beach slope do not necessarily create a diffusive beach state either. Instead, the morphological and hydrodynamic variability reside with the wave conditions propagating shoreward. In contrast, the composite beaches are described as being the most stable of the cobble beach types due to their two part morphological profile. The highly dissipative, low-sloping sand section of the beach on the seaward end have been observed to lower the wave energy within the surf zone leading to smaller amplitude waves at the shoreline. Here, the runup interacts with the steep cobble ridge on the shoreward beach front. Similar to a pure cobble beach, runup asymmetry will increase as the water infiltrates within the large grains of the cobble revetment, slowing down velocities, and potentially reducing sediment from transporting offshore. The present study focuses on both the pure sand, pure cobble beach (type 1) and mixed sand and cobble beach compositions (type 2) with respect to understanding each beach's unique swash processes, runup extents, and hydrodynamic driving mechanisms for sediment and object mobilization.

2.2 SERDP and the Munition Response Program

In 1986, a U.S. military program was created by Congress for the assessment and environmental restoration of the Department of Defense (DOD) Formerly Used Defense Sites (FUDS). FUDS activities ranged from training, weapons testing, storage/bunker use, manufacturing and handling of equipment, training accidents, combat sites, and areas containing sunken vessels. While some properties remain in the possession of the DOD, others are converted for private or public use. Many of these sites are concentrated along the coast or include adjacent water environments such as ponds, lakes, rivers, and estuaries. Thousands of sites have been identified as containing unexploded ordnances (UXO) or “munitions” thereby creating a great potential risk to the environment and to human health (SERDP, 2010). In response to this threat, the Strategic Environmental Research and Development Program (SERDP) Munitions Response Program supports the development and demonstration of technologies that can detect, characterize, and remediate munition contaminated FUDS sites. This includes assessing the risk for munition encounter based on the quantity, type, size, corrosion/contamination and re-exposure of munitions.

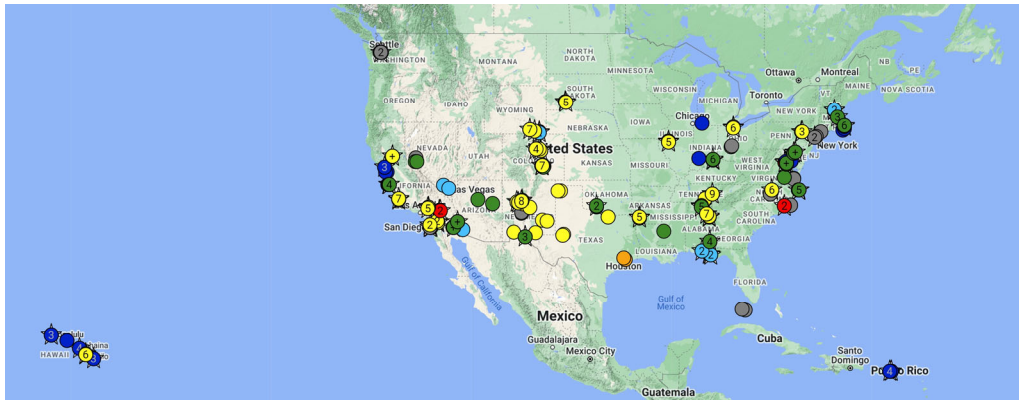


Figure 1: Munitions Response project Locations (SERDP and ESTCP, 2022)

Munition response is generally more difficult underwater. Munitions residing in underwater environments are prone to extreme forcing via waves, currents, and sediment transport. Furthermore, the nearshore region contains four main zones (shoaling, breaker, surf, and swash), each with unique hydrodynamic differences, beach development, and therefore varying mu-

munition behavior. Understanding the probability for munitions to mobilize, become partially or fully buried, and/or the direction (onshore or offshore) of the net migration stems from accurately addressing the forcing mechanisms within each zone, and the respective morphological progression. As such, at the center of the munition response effort was the development of the Underwater Munitions Expert System (UnMES), which is a probabilistic expert system used to predict burial, migration, and the re-emergence of munitions in the coastal, estuarine, freshwater, and riverine environments (SERDP, 2018). The UnMES assessments are a function of the forces required to mobilize an object and was designed for wave-dominated environments over sandy bottoms. In general, object mobility and burial have been parameterized through the dimensionless Shields parameter (θ), the Keulegan-Carpenter number (KC), the relative burial depth (B/D), object shape and object density (ρ_m). The Shields parameter is one of the most significant parameters for object mobility in terms of sediment transport and provides insight into the initiation of object motion. The threshold for motion will occur when the sum of the mobilizing forces acting on the object exceed the sum of the stabilizing forces

$$\theta = \frac{\tau_b}{(\rho_s - \rho_w) g d_{50}}, \quad (1)$$

where ρ_s and ρ_w are the densities of the sediment and water respectively, g is the gravitational acceleration, and d_{50} is the median sediment grain diameter. The bed shear stress (τ_b) is a measurement of the frictional forces of moving water or fluid acting against the bed of the channel calculated as $\tau_b = 0.5 \rho_w f u^2$, where f is the friction coefficient and u is the characteristic fluid velocity.

Other geological affects on munition motion include bedform migration, subsurface resistant layers, and large-scale erosion or deposition. For instance, scour will naturally occur when a large object is present on a relatively smaller grained bed, such as a munition placed on a fine-sand beach. The presence of the object, in combination with unidirectional and/or oscillatory flows, generate vortices concentrated near the bed. This can change the bottom stress around the object and initiate the onset of grain motion (Inman and Jenkins, 2005). The Keulegan-Carpenter number is a dimensionless parameter used most commonly in fluid dynamics to describe relative importance of the drag forces over the inertial forces for objects in oscillatory fluid

flows, and is defined as

$$KC = \frac{u T_s}{D}, \quad (2)$$

where T_s is the wave period and D is the munition diameter. For small values of KC , inertial forces are dominant. As such, the Shields parameter and Keulegan-Carpenter number have been compared to the ratio between the burial depth and munition diameter (B/D) for munitions that have not experienced any significant horizontal migration for a period of time while under constant wave forcing (Rennie [MR-2227], 2017).

Thus far, there has been a considerable amount of work focused on understanding object and munition behavior in and near the water through laboratory and field-based studies with the motivation of using the results from these studies to advance the methods and capabilities of the UnMES prediction model. However, munition mobility experiments have focused on sandy and muddy bottoms. In relation to SERDP projects, beach experiments have ranged from the wave shoaling region (Calantoni [MR-2320], 2014; Laundry [MR18-1180], 2018; Friedrichs [MR-2224], 2018), through to the surf zone (Traykovski [MR-2319], 2017; Traykovski [MR-2729], 2017; Puleo [MR20-1094], 2020) and into the swash zone (Puleo [MR-2503], 2017; Puleo [MR20-1094], 2020), while mud bottom experiments were conducted within estuarine environments (Trembanis [MR-2730], 2017; Trembanis [MR20-1480], 2020). Laboratory efforts of various underwater objects have studied large cobble motion as well and burial on sandy beaches under swash conditions (Voropayev et al., 2003), burial of cylinders on a sandy flat beds under oscillatory flows (Demir and Garcia, 2007; Catano-Lopera et al., 2007); the burial and initiation of motion on both a rigid and sandy bed (Rennie et al., 2017); and single swash event behavior of spheres on a sandy sloping beach (Gross and Puleo, 2019).

2.2.1 Munition mobility in the sandy shoaling, breaker, and surf zones

In the nearshore shoaling zone, the main factors increasing the potential for scour were an increased Shields parameter, small munition diameter ($D < 3$ cm), and an increase in the Keulegan-Carpenter number. Increasing the cylinder density was also found to increase the burial depth to diameter ratio (B/D) (Friedrichs [MR-2224], 2018). Other studies confirmed that the

relative density of the munition compared to the surrounding sediments will determine the burial and risk of exposure of the munition; if the munition density is greater than that of the sand, it will bury and stay buried (Calan-toni [MR-2320], 2014; Traykovski [MR-2729], 2017). Like in the shoaling zone, the burial depth was the greatest for high density munitions (Puleo [MR-2503], 2017). Munitions close to or less dense than the water saturated sediments were more prone to migration rather than burial; yet, those that migrated shoreward did not reach the swash, likely due to the reduction of wave energy on the sandy dissipative beaches. Conversely, beaches prone to contradictory phenomena such as offshore directed undertow combined with onshore waves and accelerations can result in little munition migration even in extreme surf zone conditions (Traykovski [MR-2729], 2017). Within the breaker zone, the preferred direction for migration was not quantified as munitions migrated in both an onshore and offshore manner.

2.2.2 Munition mobility in the sandy swash zone

Surrogate and inert munitions were found to be highly mobile in the swash zone, unlike those observed further onshore and, in the breaker, or shoaling zones. Factors for mobility include high fluid velocities, shear stresses, and steep foreshore slopes. In this zone, the densest objects were observed to have larger relative burial depths than the less dense objects, and burial was found to be related to the Keulegan-Carpenter number. In terms of munition migration, no relationships between either the Shields number nor the Keulegan-Carpenter number were resolved. For initially proud munitions, the migration distances were larger on steeper foreshore slopes (Puleo [MR-2503], 2017). Note, cobble beaches are typically steeper in nature, and prior to this study it was not known whether munition behavior mimics that of a purely sand. Under the same wave conditions, low density munitions migrated farther offshore than the higher density munitions. Munition migration did mimic wave runup direction but resulted in net offshore transport (Puleo [MR-2503], 2017). Interestingly, variations in munition mobility in the swash were attributed to beach discontinuities potentially caused by a pebble located a short distance away from the munition; however, the feedback between the pebble and munition mobility remain un-quantified (Puleo [MR-2503], 2017). The present study investigates the influence of mixed sand and pure cobble beach compositions on munition mobility.

Initial munition burial depth has also been investigated to determine the

potential for munitions to bury deeper or re-emerge and migrate elsewhere. Laboratory experiments investigating munition migration and burial under single swash events developed by a dambreak generated bore, rather than continuous wave interaction, showed that munitions deployed partially buried had lower object mobility numbers than those deployed fully proud (Gross, 2019). For munitions that did migrate, the horizontal migration mimicked the runup behavior during uprush and backwash and always resulted in net offshore displacement of munitions. Net onshore migration was not observed for any single swash event. To our knowledge, UnMES has not yet been validated by these observations of munitions intermittently submerged by water under swash induced turbulent conditions and would benefit greatly by the added framework of various shaped munition responses to single swash events. Furthermore, Rennie [MR-2227] (2017) highlights the role of granular sorting to be an unknown question in the UnMES probabilistic platform, again relevant to mixed grain beaches.

2.2.3 Object mobility and variability by size, shape, and density

Large cobbles and miscellaneous object behavior has also been referenced for inferring munition behavior on sandy beaches and mud bottoms. Laboratory experiments focused on object behavior under constant wave forcing over an initially flat sandy slope found that the general behavior of a large cobble on a sand bed will again depend on the density of the cobble. For low density cobble placed on a sandy slope, migration was onshore directed and described the cobble as being detached from the bed while traveling in the direction of the propagating bore. Offshore movement was associated to the cobble remaining attached and slipping along the bed. Heavier cobbles were observed as being more susceptible to getting trapped between ripple formations on the bed. Scour formation was sometimes observed around the entrapped cobble due to the velocities around the cobble having increased relative to the background flow. However, the constant movement of the ripples tended to dominate and move the crest towards and over the cobble until eventually covering it completely (Voropayev et al., 2003).

Cylindrical objects under oscillatory flow forcing on flat muddy beds showed a correlation between Shields Parameter and burial depth. However, burial time was dependent on a combination of the Shields Parameter, bed material characteristics, and the diameter of the cylinder; showing how the munition behavior is variable by munition type (i.e. density and shape),

and influenced by the bed material it resides upon. The scour and burial of flat cone shaped object (conical frustum) placed on a sandy flatbed were studied under both combined flows and for wave conditions alone. Results indicate burial depth of the conical frustums are smaller than short cylinder objects under similar hydrodynamic conditions. The truncated cone shape of the objects is believed to reduce the disruption to the flow, which decreases turbulence, and therefore sediment transport around the object typically responsible for scour (Cataño-Lopera et al., 2011). This raises the question on if turbulence would be increased in the presence of conical frustums or small cylindrical objects on a beach composed of mixed grain compositions, to which their relative profile on the bed might be smaller than when placed on a pure sand composition, making the munitions more susceptible to mobilizing forces. Lastly, laboratory experiments examining a variety of munition types found that for current-induced scour, smaller cylinders ($D < 3$ cm) and tapered shape objects buried more easily than large cylinders ($D > 8$ cm). However, predicting if motion would dominate over burial was contingent upon the current reaching incipient motion speeds prior to the start of scour around the object (Rennie et al., 2017).

2.2.4 Munition Mobility Related to Mixed Grain Beaches

The probabilistic nature of munition response has been quantified extensively through laboratory designed constant wave forcing. However, results are limited to beaches/beds of frictionless, sand, or muddy compositions. Yet, nearly 24% of Formerly Used Defense Sites containing military munitions are in the nearshore coastal zone with dominant cross-shore compositions of sand/gravel-sand and gravel/gravel-sand sediments. Figure 2 shows a cluster of munitions washed up on a beach after a storm. Notice the sediments around these munitions are not sand alone, rather they contain a mixture of sand, shells, cobble, gravel, and rock. Mixed grain beaches behave differently than uniform composite beaches which means the potential risk of munition migration and exposure in these environments has been unpredictable, and until now, there were no SERDP munition response program projects addressing munition mobility on mixed grain beaches. Thus, leaving the influence of heterogeneous sediment properties on munition response recondite.



Figure 2: WWII munition remnants scattered on a mixed grain beach after a landslide in 2012 (Pow, 2012).

Ultimately, the presence of mixed grains on the beach could change the importance of various components in the established force balance used to quantify munition mobility, where the sum of mobilizing forces must outweigh the sum of stabilizing forces for the munition to move. On mixed grain beaches 1) the slope of the beach will be greater than sandy beaches, 2) the drag force may be reduced compared to sandy beaches due to the armoring affect, 3) the lift force may be greater due to the increased flow accelerations in both up-rush and backwash events compared to sandy beaches; each could feedback into influencing the time varying horizontal pressure gradient exposure of the munition. Finally, the morpho-hydrodynamic feed backs on mixed-grain beaches are more complicated than those on sandy beaches. The presence of larger grains and granular sorting may influence the flow acceleration gradients on the beach. Such variability could lead to discontinuities that may influence munition exposure, mobility, and burial.

Pure cobble and mixed cobble beaches encourage more energetic waves to reach the shoreline, so the question arises, during rapid onset of high wave energy conditions, will low- and high-density munitions migrate instead of bury? This question is relevant to pure sand, pure cobble and mixed sand and cobble systems. Furthermore, will runup extent reach munition locations on the beach foreshore? If possible, will these associated velocities and water depths be enough to induce motion since horizontal runup on a cobble beach is described as having the highest energy of the bore being associated to a relatively thin layer of water (that approaches or is equal to zero) at the front. Fortunately, extensive research investigating and quantifying sediment transport on pure sand, pure cobble, and mixtures of cobble and sand beach compositions exists; thus, can predicting or measuring the net sediment transport direction and quantity after individual swash events aid in predicting the direction of munition horizontal migration (offshore or onshore), and munition burial depth and type (scour or morphological)? To begin to address these questions, the primary objective of the proposed work was to classify and compare the vulnerability of munition migration, exposure, and burial between 100% pure homogeneous beaches (sand or cobble) to two mixed grain beach compositions with varying sand to cobble ratios. Within this goal were three sub-objectives:

1. Test munition mobility, exposure, and burial response to swash bore impact on laboratory scale mixed grain beach compositions (30% cobble and 50% cobble) and compare results to purely sand and cobble experiments.
2. Test three surrogate types similar in shape, density, diameter, and length to those residing in the nearshore munition contaminated FUD environments.
3. For each beach composition and munition type, experimentally and numerically determine the influence of beach state (mild, intermediate, and steep) on swash velocities and corresponding impact to munition mobility.

To achieve these goals a double-dambreak flume experiment was conducted (Section 2). Water depths, beach profile, horizontal runup extent, instantaneous bore front velocities, and intrabore near-bed flow velocities were measured and are described in Section 2 and Section 3. To supplement these measurements, several numerical experiments based on a non-hydrostatic

phase resolving model were simulated (Section 3). In Section 4, the sediment transport regimes of the four beach compositions are discussed. Maximum object mobility numbers achieved during the laboratory double-dambreak flume experiment are compared with observed critical object mobility numbers and the numerical simulation results (Section 4). The main conclusions are summarized in Section 5.

3 Methods

3.1 Dambreak Swash & Experimental Design

In collaboration with SERDP project Puleo [MR20-1094] (2020), the experiment was designed to utilize the same swash events, surrogate munitions (sUXO), and trial configurations. As such, experiments were performed at the University of Delaware's Center for Applied Coastal Research (CACR) Facility during the summer of 2021. An artificial, permeable beach was constructed in a small-scale wave flume (33.0 m long, 0.6 m wide and 0.77 m deep) designed with glass side walls that are aligned with an accuracy of ± 0.5 mm (CACR, 2022). The beach was 5 m long and 0.7 m high, with a 1:7 beach slope. At the seaward end of the flume was a reservoir of water that when released would generate a highly repeatable, double-dambreak bore that traveled up and down the beach (Fig.3). After the water receded back offshore and into the reservoir opening, a third gate approximately 2 m offshore of the beach toe, is dropped and prevents the reflected bore from propagating back onshore.

The flume reservoirs are each 1 m long and supported by 0.005 m thick aluminum gates, each equipped with an actuating mechanism used to release the gates along with the body of water behind them. The gates are connected to a lever arm with a 40 kg mass attached at the far end. Each gate is lowered into a sealed position, and locked within a catch. An Arduino time-controlled remote trigger would actuate a solenoid to release each gate catch, and thereby allow the gates to rise rapidly. The gates could be released simultaneously, or with a delay period between the front and back gates. Adjustments to this delay could produce a variety of bore-bore interactions most prevalent in the swash zone. For the current study, the goal was to simulate the highest energies possible by this setup. To do so, a simultaneous gate release (0 s delay) was used for all trials.

Previous dambreak experiments have demonstrated that adding an ambient water level in the flat section of the flume can alter the behavior of the bore and effective downstream wave formation generated by the dambreak (STANSBY et al., 1998; Chen et al., 2016; Dai et al., 2017). For example, a depth ratio of 0.1 (ambient water level to reservoir water level) can result in a large downstream plunging wave, while a ratio of 0.45 shows the formation of a wave similar in form to a spilling breaker (STANSBY et al., 1998). This experiment was designed to sustain a depth ratio of 0.083. The initial water

levels in reservoir 1 and reservoir 2 (Fig.3) were maintained at 0.58 m for every trial and an ambient water level held at 0.05 m. As such, an initial “mushroom formation” erupts from the front reservoir gate and plunges forward forming a downstream bore similar in shape to a plunging breaker wave. The bore will propagate 3.4 m from the gate to the beach toe before colliding with the foreshore and forming the experimental swash uprush and backwash velocities that eventually make impact with the deployed munitions.

Maximum intrabore near-bed swash velocities resolved at the toe were between 1.68 m/s and 1.82 m/s, which are comparable to those encountered in the field for gently slopping beaches (Masselink and Puleo, 2006). Experimental scaling of sediment diameters and sUXO sizes were therefore ignored. Note, these velocities are approximately half a second after the EMCM sensor head was completely covered by water. Maximum velocities at the time of initial contact are expected to be closer to 2 m/s. These velocities are similar to single-dambreak experiments on impermeable slopes of various roughness (O’Donoghue et al., 2010; Dai et al., 2017), and to those observed in previous CACR double-dambreak experiments under similar swash conditions (Gross and Puleo, 2019).

Factors contributing to intrabore near-bed swash velocities can in part be attributed to the dissipative and reflective properties of the beach, which in themselves can be correlated to the steepness of the beach, and to sediment size. For instance, dissipative beaches have been characterized as having a low slope over a wide sandy cross-shore face. Conversely, reflective beaches are steeper and are typically comprised of pure cobble. For either case, there can be a wide range of beach slopes and sediment compositions that alter the hydrodynamic properties of the double-dambreak and as such potentially alter munition mobility as well. Since the present study did not modify the 1:7 slope of the artificial beach for the flume experiments, four different beach compositions were compared.

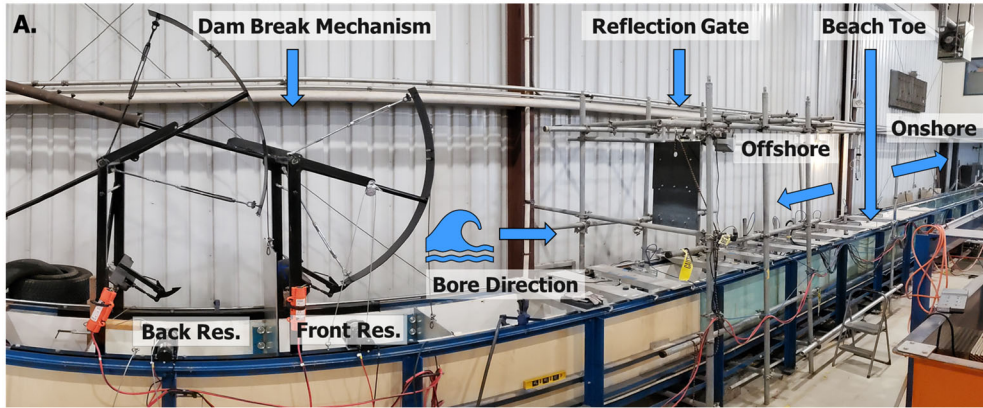


Figure 3: University of Delaware's Center for Applied Coastal Research Double-Dambreak Small-Scale Wave Flume.

3.2 Beach Compositions

Mixed beach compositions can include sediments such as mud, fine sand ($100 \mu\text{m} < d_{50} < 2 \text{ mm}$), shell, gravel ($2 \text{ mm} < d_{50} < 64 \text{ mm}$), and even small boulders ($d_{50} > 256 \text{ mm}$) (Coates and Daamgard, 1998). Notably, this sediment variety means the distribution can vary along the cross-shore, along-shore, and vertical beach profile. Mixed beaches can also vary temporally, with composition change happening as frequent as tidally, daily, monthly, and seasonally (Pontee et al., 2004). After reviewing 158 sediment, Coates and Daamgard (1998) concluded that a clear definition for what encompassed a uniquely "mixed sediment" beach was not possible. However, foreshores resembling the mixed cobble (type 2) and composite cobble (type 3) beaches were recognized. Along with this, they found the d_{50} for the sand fraction was around 0.3 mm and the cobble fraction ranged between 10 mm and 20 mm . The percentage of sand fraction was between 20% and 30% (but could be much higher) and increased approximately 10% beyond 1.5 m below the surface of the bed (Coates and Daamgard, 1998). The present study focused on mixed beaches of sand and cobble only, with the goal of recreating a fully and homogeneously mixed beach in the horizontal and vertical beach profiles. As such, four different beach compositions were created: 1) 100% sand, 2) 100% cobble, 3) 30% cobble/ 70% sand and 4) 50% cobble/ 50% sand.

The cobble used in this experiment was specified as polished-black landscape rock with a median diameter (d_{50}) of 6.35 mm - 12.7 mm. The sand was flint silica (quartz) fine grain sediment with a d_{50} of 0.2 mm. Both grains were composed of densities close to 2650 kg/m³ (silica, granite, basalt). The proper ratio for the mixed compositions was created and mixed thoroughly in batches. To achieve a homogeneously mixed composition in each batch, the specific volume ratio of sand and cobble was placed into a concrete mixer, spun for 2 minutes, and emptied into the flume. Conversely, the 100% sand and 100% pure cobble was delivered in 25 kg and 18 kg bags (respectively) that did not require any sorting or modification.

To create the beach, each batch of material was manually placed within the flume at the toe then spread onshore to create a 0.05 m layer of material. The material was saturated and manually packed to fill large voids. Note, the flume walls were equipped with thin metal rails that slope onshore from the toe at the 1:7 beach slope and were left exposed while filling the flume. Placement and packing of the sediment was repeated until the beach section of the flume was completely filled to the height of the rails. A 0.1 m wide x 0.59 m long x 0.03 m thick metal block attached to a 1 m long pole and pulled over the flume rails was used to level the bed. This process of leveling the beach to the desired starting profile was also used when resetting the beach to the desired 1:7 slope at the start of a new experimental series (Fig 4).



Figure 4: Shown left to right are the four varying beach compositions used throughout the experiment: pure sand, pure cobble, 30% cobble, and 50% cobble on a 1:7 (8) sloping beach. Sand was uniformly fine, ϕ 0.2 mm diameter and the cobble was 12.7 mm smoothed, black, beach cobble.

3.3 Surrogate Munitions

Three cylindrical sUXO with varying sizes and densities were tested during the experiment including 20 mm and 40 mm cylindrical projectiles and a 40 mm-Rank 2 cylindrical projectile with bio-foul covering. These munitions were developed by Puleo [MR20-1094] (2020) and loaned to us for the mixed-grain experiments. Each munition is classified according to a specific munition ID, and vary in density (ρ_m), diameter (D), and length (L). Munition attributes are outlined in Table 1 and Fig.5. Originally, all sUXO were silver and black in appearance but were later painted half green and half red along the longitudinal axis (nose to tail). The colors were selected to enhance LiDAR detection of the munitions used to track sUXO behaviors such as horizontal migration, roll (spinning about the nose), yaw (sideways movement about the nose), and pitch (up or down motion about the nose), and burial.

Table 1: sUXO Attribute Table

Surrogate Munition sUXO	Munition ID	Shape	Density ρ_m g/cm^3	Diameter D m	Length L m
20 mm	M20	Cylindrical	7.99	0.02	0.07
40 mm	M40	Cylindrical	5.72	0.04	0.2
40 mm - Rank 2	M40R2	Cylindrical w/ bio-foul covering	2.46	0.7-0.9	0.23

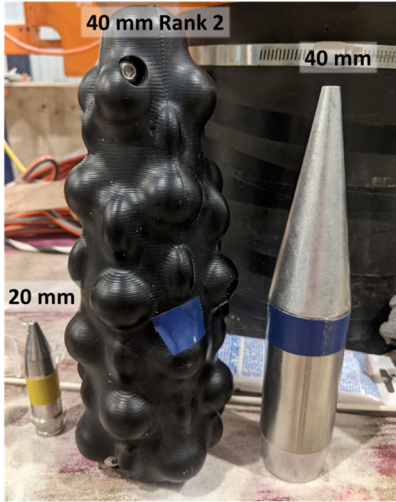


Figure 5: From left to right are the M20 (20 mm), M40R2(40 mm with covering), and M40 (40 mm) surrogate munitions shown with original exterior and prior to being painted red and green.

3.4 Experimental Configurations

Experimental configurations are broken down by beach composition and munition type. For each beach composition, a hydrodynamic series of five continuous trials is completed without resetting the bed, where a trial corresponds to one double-dambreak swash event. As such, the altered morphology from the previous double-dambreak is left untouched until the start of a new series, at which point the beach is reset to the original 1:7 slope. Replicas of three munition series were conducted per beach composition and munition type combination, resulting in a total of 180 trials. During each trial, two sUXO of the same type were deployed simultaneously. A munition series began by resetting the beach to the 1:7 slope. Next, one sUXO was placed at $X = 1.5$ m ($Z = 0.21$ m) and the another of the same type at $X = 2.5$ m ($Z = 0.36$ m). The munitions were deployed proud (0% buried) with the green-face oriented up. Physical measurements of the two sUXO positions (nose and tail) on the beach were manually collected before and after each trial.

Lastly, a series of hydrodynamic trials (absent of munitions) were also performed to quantify the double-dambreak hydrodynamics of the four beach

compositions. The sUXO were removed to avoid objects close to the beach face from colliding with the hydrodynamic cart sensor heads. Due to the repeatability of the double-dambreak mechanism, only one hydrodynamic series (five back-to-back double-dambreaks) were conducted for each beach composition. Hydrodynamic experiments involved positioning twelve station carts at pre-set horizontal positions above the flume (Fig.11). The pressure and moisture sensors located within the beach collected measurements during these trials as well. Station carts were rolled back into their stored locations after the trial to acquire the pre- and post- LiDAR scans to collect measurements of the beach profile. They were then stationed back at the pre-set positions before the next trial. Due to the placement of the carts, the LiDAR field of view (FOV) were completely obstructed and not useful in capturing the bore dynamics during the hydrodynamic trials. Thus, analysis of the bore transformation was carried out with data collected during the munition trials and the interactions between the munition with the incoming bore were assumed negligible.

Table 2: Experimental Configurations

Beach Composition	Series Type	Munition ID	# Series	# Trials (per series)	Total Trials	Burial (%)
100% Sand	Munition	M20	3	5	15	0
-	Munition	M40	3	5	15	0
-	Munition	M40R2	3	5	15	0
-	Hydrodynamic	-	1	5	5	-
100% Cobble	Munition	M20	3	5	15	0
-	Munition	M40	3	5	15	0
-	Munition	M40R2	3	5	15	0
-	Hydrodynamic	-	1	5	5	-
30% Cobble	Munition	M20	3	5	15	0
-	Munition	M40	3	5	15	0
-	Munition	M40R2	3	5	15	0
-	Hydrodynamic	-	1	5	5	-
50% Cobble	Munition	M20	3	5	15	0
-	Munition	M40	3	5	15	0
-	Munition	M40R2	3	5	15	0
-	Hydrodynamic	-	1	5	5	-

3.5 Instrumentation & Signal Processing

3.5.1 Hydrodynamic measurements

Instrumentation to measure water depths and water velocities were deployed above the flume on station carts or mounted directly to the flume walls (Fig.6). Ultrasonic distance meters (UDM), acoustic Doppler profiling velocimeters (ADPV), electromagnetic current meters (EMCM), and a pressure sensor array (PSA) were mounted to station carts, at variable distances above the bed, for swash hydrodynamic analysis. Station carts were deployed in a horizontal array at the locations indicated in Appendix A, and shown in Fig.11 (C). For munition mobility analyses, station carts were tucked away to provide an unobstructed FOV for the LiDAR while the interior pressure and moisture sensors remained in use. The buried and hydrodynamic station sensors were sampled at 100 Hz using a National Instruments data logger.

Recording laptops were synchronized with the Dimension4 software via a local network time server that received GPS time corrections from a Garmin antenna and Tac32.



Figure 6: Hydrodynamic station carts positioned at pre-set locations along the length of the flume. Visible carts are equipped with an UDM, ADPV, and EMCM.

Ultrasonic Distance Meters

Banner ultrasonic distance meter raw voltages were converted to distances through a calibration between known voltage values for the sensor to a measured distance. Water depth from UDM measurements was estimated by subtracting the UDM measurement of distance to the reflective surface from the surveyed sensor height. The bore front was identified by the UDM as the time when the sensor first detected a change in the water surface elevation. The UDM identified bore front was then used to synchronize the trials with the Velodyne LiDAR measurements by using the time the UDM bore front crossed the beach toe ($X = 0$ m). At $X = 3.45$ m (sensor cart H12) measurements during backwash were unreliable, likely due to the very small water depths, and were therefore omitted.

Electromagnetic Current Meters

Intrabore near-bed velocities were collected with a Valport electromagnetic current meter (EMCM) positioned 2 cm above the bed. The UDM sensor deployed alongside the EMCM was used to determine when the sensor head was completely submerged. Depending on the water depth, EMCM velocity measurements typically stabilized 0.3-0.4 s after the re-immersion point, only velocities thereafter were used for interpretation. Additionally, outliers, dropouts, and spikes were removed and smoothed over.

Pressure Sensors and Moisture Sensors Six pressure sensors and seven moisture sensors were buried in the interior of the 1:7 beach during construction and used to infer pore pressure gradients and potential infiltration rates between the beach compositions. The Druck 1830 PCDR pressure sensors were deployed in a vertical pair at three horizontal locations. (Table 4). Each pair included two pressure sensors secured to a 2 in metal screw with their tips spaced 5 cm apart, and the body of the sensors fastened perpendicular to the screw. Placement of the pressure sensors needed to capture the transient bore without interfering with the flow of the infiltration. To do so, the screw was placed vertically upright in the beach with the tips perpendicular to the flume walls and as close to the center of the flume as possible (Fig.7). The 5 cm burial depth was measured from the 1:7 leveled bed and the tip center point of the uppermost attached pressure sensor on the screw. All cable was cleared from the sensor heads and buried deep in the positive X direction along the outermost flume wall. Meter TRIO moisture sensors were buried at the same heights as the pair of pressure sensors but away from the tips with their pins pointing up-slope, and running parallel with the flume. An extra moisture sensor was buried alone at $X = 3.9$ m.



Figure 7: Beach creation process showing the steps for burying the pressure and moisture sensors.

The Druck 1830 pressure sensors used in this experiment were first converted to mm of water through a calibration between known voltage values for each pressure sensor to a known maximum pressure output determined prior to burial. The pressure data was processed to identify the pore pressure gradient differences between the pure cobble, and mixed grain beach compositions. For the pair of buried pressure sensors located at $X = 1.49$ m and $X = 2.6$ m, several filtering methods were attempted to despike the pressure data such as applying a high pass filter, low pass filter, band-pass filter, moving mean filter with various running average values, and any combination of the four. To avoid over smoothing the unfiltered pressure data (blue), the selected processing method was to simply filter using a 100Hz moving mean

filter (red) (Fig.8). Pressure gradients were calculated by taking the difference in processed pore pressure data between the pair of deployment pressure sensors and dividing by the difference in elevation (5 cm) between the two pressure sensors. The same UDM time offset was applied to the pressure time series and used to synchronize the trials.

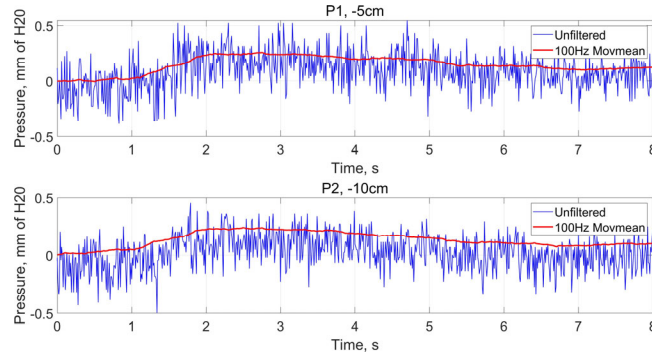


Figure 8: Example of unfiltered (blue) versus filtered (red) pore pressure sensor data for sensors buried at $X = 1.49$ m. Top row shows the upper (P1) pressure sensor buried 5 cm below the bed and the bottom row shows the lower (P2) pressure sensor buried 10 cm below the bed.

3.5.2 LiDAR

Two types of LiDAR were used in this experiment: the Velodyne HDL-32 and the Intel RealSense L515 Camera. The Velodyne HDL-32 LiDAR was used for beach profile measurements, as well as to track the bore propagation up and down the beach. The RealSense cameras were used to monitor munition motion during the swash event. As such, a total of 3 scans were conducted per trial to which two types of LiDAR data were obtained: stationary and nonstationary data. Stationary data corresponds to the measurements where there is no variation in time (i.e bore propagation). These 20 s duration scans collected beach profiles (Velodyne) before and after the trial. Nonstationary scans were 40 s and occurred during the swash event to track bore propagation, water depths, runup, exposed beach regions (Velodyne) and munition behavior during the event (RealSense).

Velodyne HDL-32 LiDAR The Velodyne HDL-32 LiDAR is the larger of the two systems with an approximate height of 144 mm and a diameter of 85 mm. The sensor is a rotating LiDAR consisting of an emitting/receiving optical window with 32 individual, one-dimensional laser rangefinders. The vertical span of the 32 rangefinders is between -30° and $+10^\circ$ from its optical center. Each laser is stationed to a panel that rotates 360° about the vertical Z-axis (Chan et al., 2013). The optical center (0, 0, 0) is where relative distances are referenced 90.81 mm from the sensor bottom. Timing to fire

and recharge all 32 lasers is fixed at $46.08 \mu\text{s}$ per firing cycle. For data collection, there are 12 firing cycles per data packet. The number of frames per second (fps) is controlled by setting the rotation speed or rotations per minute (RPM). One rotation of the instrument correlates to a single “frame” of data and begins and ends at the 0° azimuth (unsigned integer representing a FOV angle in hundredths of a degree (Velodyne, 2017)). The RPM can range from 300 to 1200 in any increment of 60 and is maintained to within ± 3 RPM. Due to the fixed firing sequence of the LiDAR, increasing the sensor speed also increases the horizontal (azimuth) resolution of the sensor.

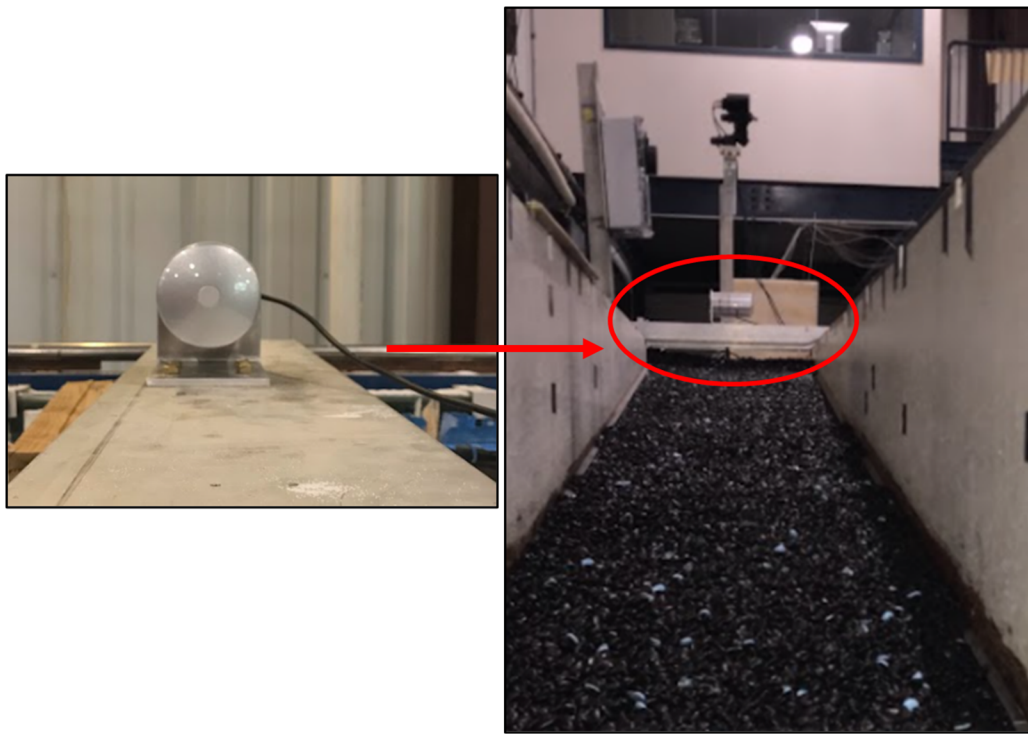


Figure 9: Velodyne LiDAR mounted horizontally in the flume at $X = 5.1 \text{ m}$

Frame outputs from the Velodyne LiDAR are three-dimensional point clouds generated by the laser’s detection of a reflection, known as a laser return. There are three return options: Strongest, Last, and Dual. In Single return mode, a laser pulse will detect one reflection/measurement and record it as the Strongest and Last return measurement option. Beam divergence, or beam spreading, occurs for all laser shots and will increase with growing

distance from the laser. Depending on the range of the pulse, the beam could be large enough to detect multiple reflections. Typically, closer reflections will have stronger returns, (this is not always the case if reflections are generated on reflective or bright surfaces). If multiple reflections are detected, alternative modes such as "Strongest" or "Last" allow the user to specify that only the strongest reflection or the last (slowest time) reflection, be recorded (Single Return Mode). The user can also obtain both measurements with the Dual Return mode capability. In this case, the sensor will record both returns if the separation between the two points is equal to or greater than 1 m. Measurement speeds span between 695,000 and 1,390,000 points per second depending on if single or dual mode is enabled (Velodyne, 2017). The Velodyne HDL-32E is specified to have a measurement range of 80-100 m with 0.02 m accuracy.

The Velodyne LiDAR is used in this experiment for detecting the bore transformation in real time, and bathymetric changes between consecutive trials. It is mounted 0.83 m above the flume bottom, 5.1 m onshore of the toe, and oriented horizontally to scan along the length of the flume with the optical window aligned with the center line (0.3 m from either flume wall) (Fig.9). The Velodyne is also programmed to focus its measurements to within the flume by setting the starting and ending azimuths to 180° and 360°, respectively. As such, the collective laser swath is reduced to about 20 of the 32 individual rays. Given how all 32 lasers provide a 40° FOV from the optical center, the FOV is reduced to about 16 degrees, now oriented such that the rays scattered along the width of the flume. The Velodyne LiDAR was programmed to sample at 1200 revolutions per minute, correlating to a frame rate of 20 Hz and horizontal resolution of 0.3° per firing cycle. Lastly, dual output return mode is engaged. The selected Velodyne LiDAR settings ensured the entirety of the swash event and bore propagation up and down the beach was recovered by the sensor at a fine temporal and spacial resolution.

Using LiDAR to measure water surfaces can be challenging, since calm water behaves like a mirror, and a return of laser light signal is obtained only if the angle of transmission incidence is perpendicular. However, the turbulent nature of the swash zone offers ample sources to generate usable backscatter, and therefore improves the rate of the return signal to the LiDAR (Blenkinsopp et al., 2010). Sources of reflected light detectable by the LiDAR include the beach, the turbulent wave front, objects and obstructions, and general ambient light sources. Post-processing is used to reduce noise, and to separate the propagating water from bed level measurements (Almeida

et al., 2015; Blenkinsopp et al., 2012; Martins et al., 2017). First, LiDAR measurements are geo-referenced for point cloud transformation; the data is also de-noised by applying a moving mean filter, down sampled, interpolated, and finally, thresholds are applied to differentiate water measurements from beach measurements. Beach profile measurements collected with the LiDAR before the bore was released are used as a baseline for separating the raw scan into two independent time series of morphological and hydrodynamic measurements. A threshold water depth is applied to the baseline measurements and applied to subsequent measurements in each frame. The time varying water surface is identified as any measurement return above the baseline profile plus the minimum water depth criteria. Any return equal to or below the baseline profile are considered to be the bed. Various threshold water depths were tested (0.5 mm up to 35 mm) and were based on the calculated noise floor of the sensor for each beach composition (Appendix C). As the threshold water depth was reduced, the number of incorrectly separated water-to-bed measurements increased. Therefore, the raw scan measurements were separated two times. Once using a 1 mm water depth threshold and again with a water depth threshold of 15 mm. Observed UDM hydrodynamic water depth measurements were used to validate the 1 mm and 15 mm threshold water depths applied for LiDAR measurement separation (large blue circles). For a complete description of the Velodyne post-processing methods the reader is referred to Appendix B.

Water surface measurements captured using the Velodyne LiDAR were used to track bore swash dynamics. The time varying bore front position was identified at each time step, and corresponds to the further onshore water surface measurement intersecting the beach profile. However, the FOV of the Velodyne LiDAR was limited and could only resolve 4.7 m up the beach. As such, maximum horizontal runup shoreward of 4.7 m could not be resolved. Manual measurements of maximum runup extent for the pure sand beach and 50% cobble beach were intermittently collected after the swash event (for miscellaneous trials) by manually measuring the estimated maximum extent with a tape measure and used as a reference between observable runup extent and runup resolved by the Velodyne LiDAR.

Munition tracking with RealSense Cameras In addition to pre-trial and post-trial measurements of the munition's nose and tail, munition tracking during the trial is achieved with the RealSense imagery capabilities. The RealSense cameras are small, lightweight, RGB integrated LiDAR systems. A row of three RealSense cameras were positioned above the flume (Fig.10)

to record munition transitions at all stages of the double dambreak generated swash over the beach profile (Fig.11). Similar to the Velodyne LiDAR, the nonstationary scans from the RealSense cameras were transformed into the flume coordinate system. Since each measurement also has an associated RGB color, munitions could be identified and tracked by color hue and intensity values specific to the green and red coloring of the painted munitions.



Figure 10: Two of the three RealSense cameras positioned above the flume, oriented downwards.

Manual tracking of munitions was performed by selecting the initial midpoint position of the munition prior to bore inundation. If migration was evident, a new midpoint was selected and was used for the sequential frame and if the munition was not visible due to turbulence, the previous midpoint was used until a new midpoint could be inferred. When only a few points with the same munition hue and intensity values were visible, the midpoint of the point cluster was selected and might not directly align with the exact midpoint of the munition. Munition center-point selection was important to try and capture migration in the most energetic parts of the bore release. The final selection of munition midpoints from each frame provided munition mobility as a function of time. Conditions such as the time of incipient motion, rotation and yaw angles prior to motion, total onshore/offshore directed migration, and the type of burial (scour or morphological) were tracked.

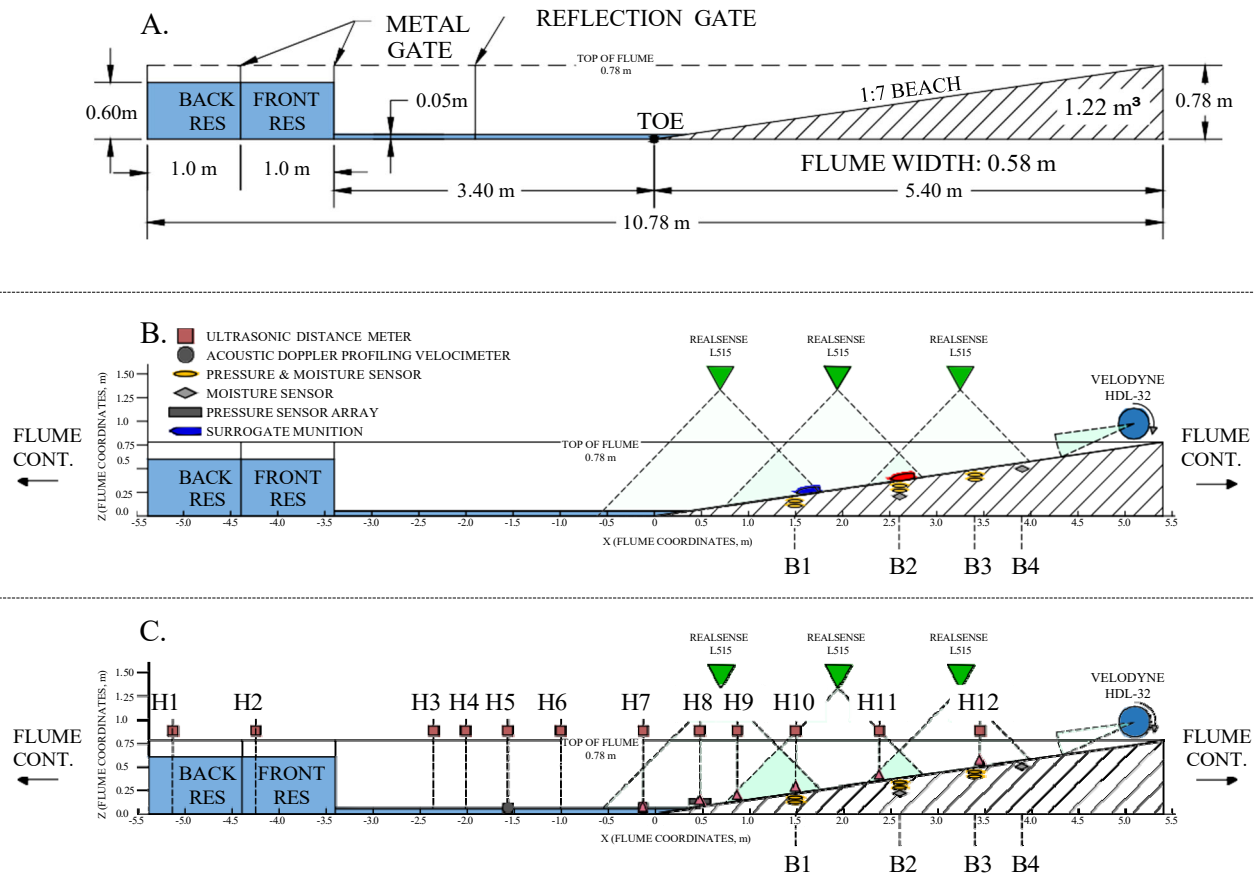


Figure 11: A. Schematic of the University of Delaware's Center for Applied Coastal Research Double-Dambreak Small-Scale Wave Flume. B. Sensor Layout for Munition Trials (initial munition placement locations also indicated with sUXO symbol). C. Sensor Layout for Hydrodynamic Trials.

3.6 NHWAVE Numerical Experiments

NHWAVE is a 3D non-hydrostatic wave model that can simulate waves, currents, and sediment transport simultaneously (Kirby and Shi, 2014; Ma et al., 2012). Non-hydrostatic depth-dependent simulations of intermediate and steep sloping beaches were performed to expand the hydrodynamic conditions of the experiment not physically tested for in the laboratory. The numerical simulations help simplify the large parameter space involving several munition types, beach compositions, slopes, and hydrodynamic forcing conditions and are used to determine the controlling factors that lead to sediment transport, and munition mobility for different beach compositions. Finally, model results place the swash event conditions of the laboratory study in the context of velocities and accelerations experienced at natural beaches.

The laboratory hydrodynamic observations served to develop and calibrate a fully unsteady numerical model for further investigation of the hydrodynamic forcing variability on mixed grain beaches. The model uses the median grain size (d_{50}) of the sediment as one of the main attributes for calibration, typically making a pure sand beach composition easier to parameterize due to the single grain size composing the beach. Accurately representing mixed grain beaches with variable sediment sizes was more challenging. To overcome this, the bottom roughness condition was included in the model parameters. NHWAVE includes two ways of specifying the bottom roughness: 1) with a bottom roughness height as part of the law of the wall formulation or 2) with a drag coefficient which uses a form drag approach. Model results suggest the simulated water surface elevation was not sensitive to the roughness parameterization. Thus, the roughness height and law of the wall formation was applied because it directly relates the mean grain size (average sediment size between sand and cobble) to the bottom friction. An example of water surface elevation and horizontal velocity snapshots of the bore propagating up the 1:7 beach slope from the NHWAVE simulations are shown in Fig.12. To aid in further understanding how munition mobility may be influenced by the change in beach slope or initial bore energy, sensitivity analyses was performed to match observations as much as possible by varying NHWAVE input parameters until modeled results were within range of the laboratory observations.

Wave dispersion characteristics are addressed in the model through the number of vertical layers specified. Iterations vary by time step and hor-

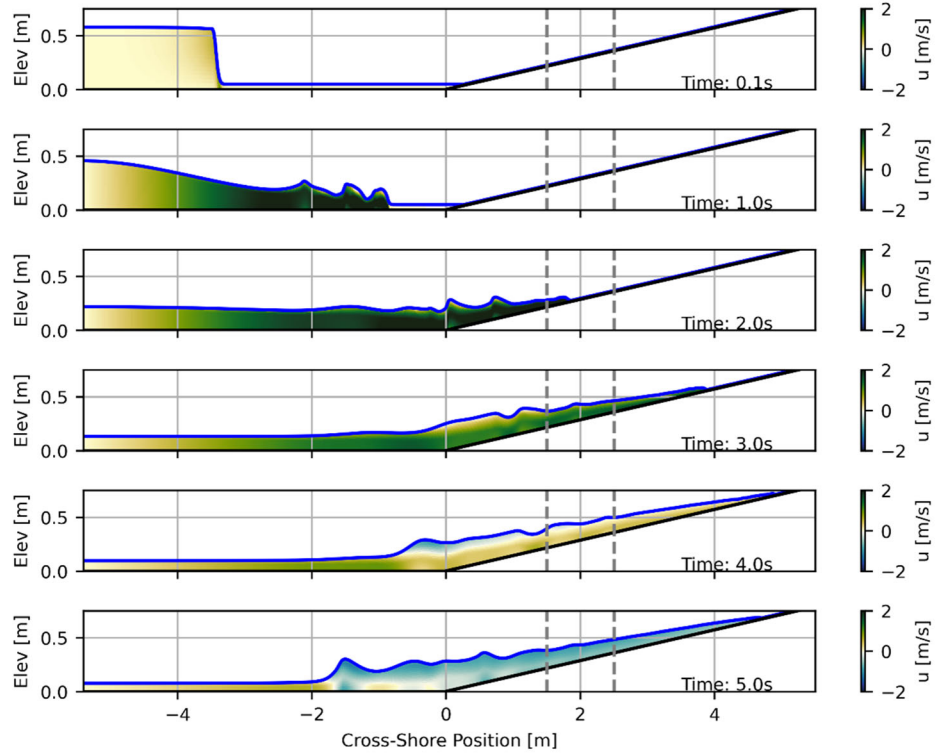


Figure 12: NHWAVE dambreak simulation showing calibrated model with 25 vertical layers and 2 cm horizontal resolution. Positive velocity indicate uprush. Downslope and upslope munition locations are shown as vertical dashed lines. Model run time (time, s) indicates the time since dambreak.

horizontal position, depending on the number of layers, the accuracy in wave dispersion characteristics could increase as the layers are increased, but the simulation speed slows down. Typically, 10-20 vertical layers produce acceptable predictions for the wave dispersion characteristics (Kirby and Shi, 2014) in non-hydrostatic model simulations, sensitivity to the number of vertical layers will be explored.

4 Results

4.1 Hydrodynamic Observations

Stationary and nonstationary measurements include water depth, horizontal runup, instantaneous bore front position, bore front velocity (U), intrabore near-bed uprush (u_u) and backwash (u_b) velocities, pore pressure gradients, and the morphological evolution of the beach. The hydrodynamic and beach morphological progression from the initial conditions measured during Trial 1 to the conditions measured during Trial 5 are used to infer the characteristics of munition mobility for single and multiple bore swash events on each beach composition.

4.1.1 Measurements of water surface elevation & water depth

The time at which the bore front reached $X = 0$ m was recorded and used to time synchronize all experimental trial results. Therefore, time denoted as $t = 0$ s, is referring to the time since the bore reached the toe at $X = 0$ m. The extracted bore front (red circle) and the uninterpolated water elevations behind the bore front (blue line) traversing over the sand beach (green profile) (during Trial 1 at various scan times is presented in Fig.13.

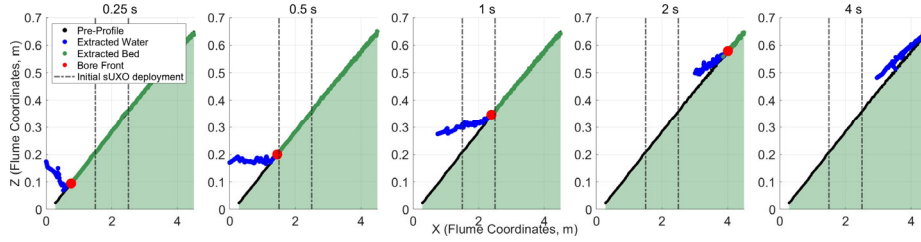


Figure 13: Separated water and bed measurements using the 1 mm threshold water depth at various times and for the pure sand beach composition.

The double-dambreak generated swash bore is highly repeatable and monochromatic. As such, swash events of the same trial number (e.g Trial 1 from all munition series) were averaged (Table 3).

Table 3: Number of trials used for horizontal runup estimates for the pure sand, pure cobble, 30% cobble and 50% cobble beach compositions.

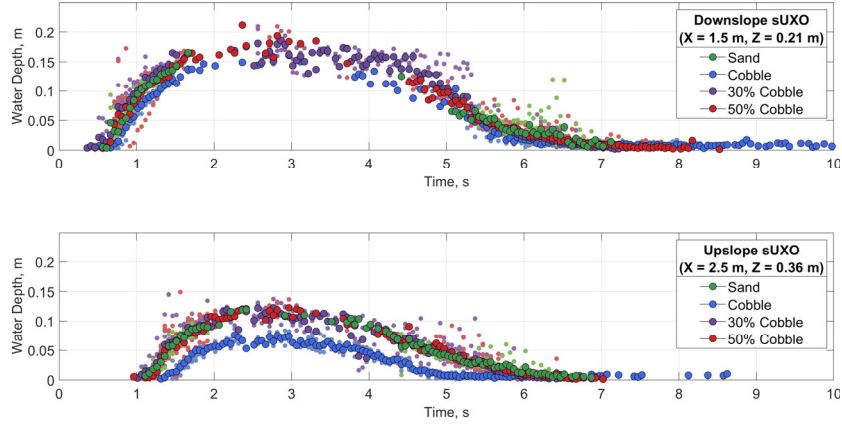
Beach Composition	Trial 1	Trial 5
100% Sand	5	5
100% Cobble	7	8
30% Cobble	10	10
50% Cobble	9	7

Depending on the munition mobility and location on the beach, the munition was observed to be unsubmerged, partially submerged, or completely submerged throughout the swash event. Ensemble averaged water depths are presented at flume coordinates $X = 1.5$ m ($Z = 0.21$ m above the toe) and at $X = 2.5$ m ($Z = 0.36$ m above the toe) during Trial 1 and Trial 5. The coordinates correspond to the munitions' initial deployment locations, herein denoted as the downslope munition and upslope munition, respectively.

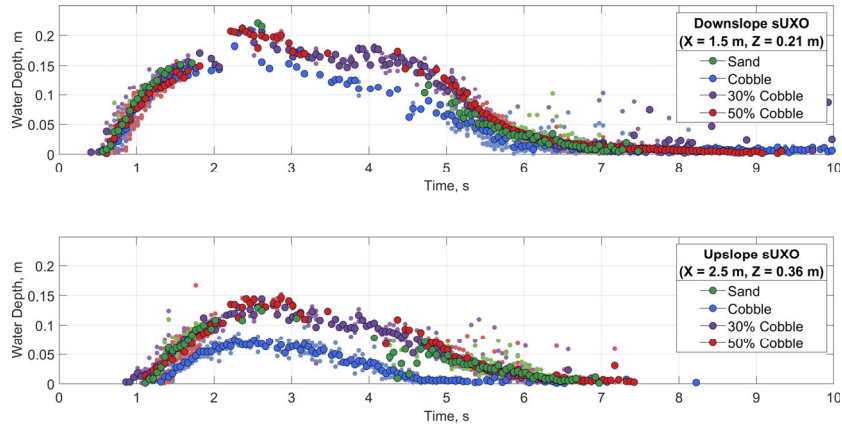
Water depth from the Velodyne LiDAR measurements were estimated by subtracting the extracted water surface measurement from the pre-trial beach profile measurements. Values measured with the LiDAR were also compared to water depths collected by the UDMs during the hydrodynamic trials for each beach composition. Since UDM station carts were not positioned directly over the initial munition deployment locations, a linear interpolation scheme was applied to the measured time varying water depths to estimate depths across the entirety of the beach. Extracted water depths from both

the LiDAR and UDM measurements were not observed to exceed 0.25 m at most locations across the beach during uprush and backwash, with the furthest downslope locations being subject to longer flow duration and deeper water levels (Fig.14).

Water depths at the downslope muniton varied the least between beach compositions. The bore front first reached the downslope muniton between 0.6 s to 0.8 s after crossing the toe (at $t = 0$ s). Maximum water depths were achieved approximately 2 s from this first impact, and ranged between 0.14 m to 0.2 m. The observed bore front reached the upslope muniton between $t = 1$ s and $t = 1.2$ s on the pure sand and mixed grain beach compositions, and at $t = 1.36$ s on the pure cobble beach. Water depths on the pure sand and mixed grain beaches were approximately 0.12 m whereas on the pure cobble beach were between 0.07 m - 0.08 m. Overall, maximum water depths during Trial 1 at the upslope muniton on the pure sand and mixed grain beaches were nearly double those observed on the pure cobble beach. Lastly, observed water depths during Trial 5 at the upslope muniton increased by approximately 0.02 m for the sand and mixed grain beaches. However, observed water depths did not change at the upslope muniton on the pure cobble beach during Trial 5.



(a) Trial 1



(b) Trial 5

Figure 14: Trial 1 (a) and Trial 5 (b) individual (small, filled circles) and ensemble averaged swash depths (large, filled circles) at initial sUXO deployment locations. Results depicted are from the extracted water surface measurement using the 1 mm threshold water depth. Beach composition is separated by color and defined in the legend.

Horizontal Runup Runup was measured with the Velodyne LiDAR and validated with manual measurements using a tape measure. Manual runup extent measurements on the pure sand beach ranged between 4.94 m to 5.02 m with a mean of $\bar{X} = 4.98$ m and 4.33 m to 4.73 m ($\bar{X} = 4.62$ m) on the 50% cobble beach. Manually measured runup maxima were not collected for the pure cobble and 30% cobble beach trials. Throughout the experiment, the pure cobble horizontal measurements remained within the FOV of the Velodyne. As such, the average maximum resolved horizontal runup from the 1 mm threshold water depth dataset was 3.49 m for Trial 1 and 3.46 m for Trial 5. Typically, the runup extent extracted using the 1 mm threshold water depth were not fully resolved on the pure sand and mixed grain beaches. This is visible in the runup extent for the individual trials as a noticeable flatline at $X = 4.68$ m where the runup values remain stagnant for approximately 2 s (gray circles in Fig.15). The 15 mm threshold water depth were fully resolvable with curves more parabolic in shape. Based on the manual runup measurements however, both the 1 mm and 15 mm threshold separated surface measurements underestimated the horizontal runup extent on the pure sand and mixed grain beaches. Therefore, a least-squares polynomial was fit to the averaged horizontal runup extent to estimate maximum runup.

Derived curves using the polynomial fit include measurements from the start of uprush at $X = 0$ m to the peak resolvable runup extent and a single measurement at the backwash initiation point. Note, the polynomial fit curves are used to extract maximum runup extent and are only representative of the bore front during uprush and moments before flow reversal. Trends in backwash behavior were taken from the extracted LiDAR measurements but proved more difficult to capture than the uprush due to the backwash water depths being very thin, the position of the LiDAR, obstructions in the flume, and a shadow cast by the bore in the foreshore. Another source of uncertainty in the LiDAR measurements was due to the fact that the swash did not completely recede. Depending on the beach composition, the water would remain on the beach at around $X = 1$ m for the duration of the backwash and prevented detection of the bore downslope and offshore of 1 m. Ensemble averaged horizontal runup extent from all available Trial 1 and Trial 5 munition series is presented in Fig.15. Both the 1 mm and 15 mm extracted runup from the Velodyne LiDAR is presented such that the shaded plot area depicts a region where runup is expected to have occurred. Fig.15 subplots a, b, and d, contain a horizontal line defining the runup

extent values observed for the pure sand, pure cobble, and 50% cobble beach compositions.

UDM bore front values (bright blue circles in Fig.15) at station carts located over the beach were used to help validate the extracted water surface measurements from the Velodyne LiDAR. Observed UDM runup measurements align with the 1 mm uprush measurements and best fit curve.

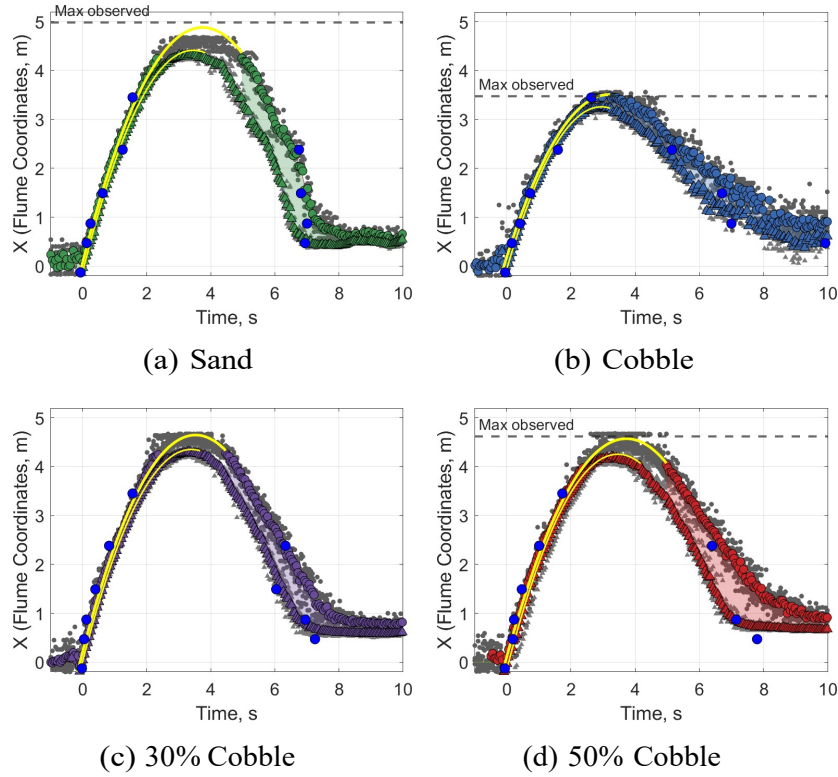


Figure 15: Horizontal runup extent extracted from the Velodyne LiDAR water surface measurements using the 1 mm and 15 mm threshold water depths. Polynomial best fit curves (yellow lines) and UDM extracted runup positions (blue points) at station carts 9, 10, 11, and 12 are overlaid on top. Dark gray circles represent the extracted runup measurements from the 1 mm minimum water depth criteria and light gray triangles from the 15 mm minimum water depth criteria for all Trial 1 scans, while colored circles and triangles represent the ensemble average of the Trial 1 scans. The shaded region between circle and triangle data is the region where uprush and backwash likely occurred.

The polynomial fit curves for all beach composition show subtle variability in the runup extent and runup duration as trials progressed between Trial 1 and Trial 5. Maximum predicted runup on the sand beach was the largest for all five swash events. Estimated maximum runup from the polynomial fit curves shows that as the percentage of sand in the beach increased, runup extent was observed to propagate further shoreward. Conversely, the 100% cobble beach had the smallest runup extent, but longest net runup duration (uprush + backwash) out of the four beach compositions, and was independent of trial number (Fig.16). The polynomial fit curves and the ensemble averaged horizontal runup trajectories during Trial 5 are temporarily lagging behind the Trial 1 runup trajectory for the pure sand, and mixed beaches. Conversely, the runup measured during Trial 5 on the pure cobble beach slightly lead the runup of Trial 1. This pattern is visible within both the ensemble averaged and polynomial fit runup curves. However, the lags are small, maybe almost negligible. Instantaneous bore front velocities are then extracted from the horizontal runup by taking the gradient of the bore position with respect to time ($U = dx/dt$).

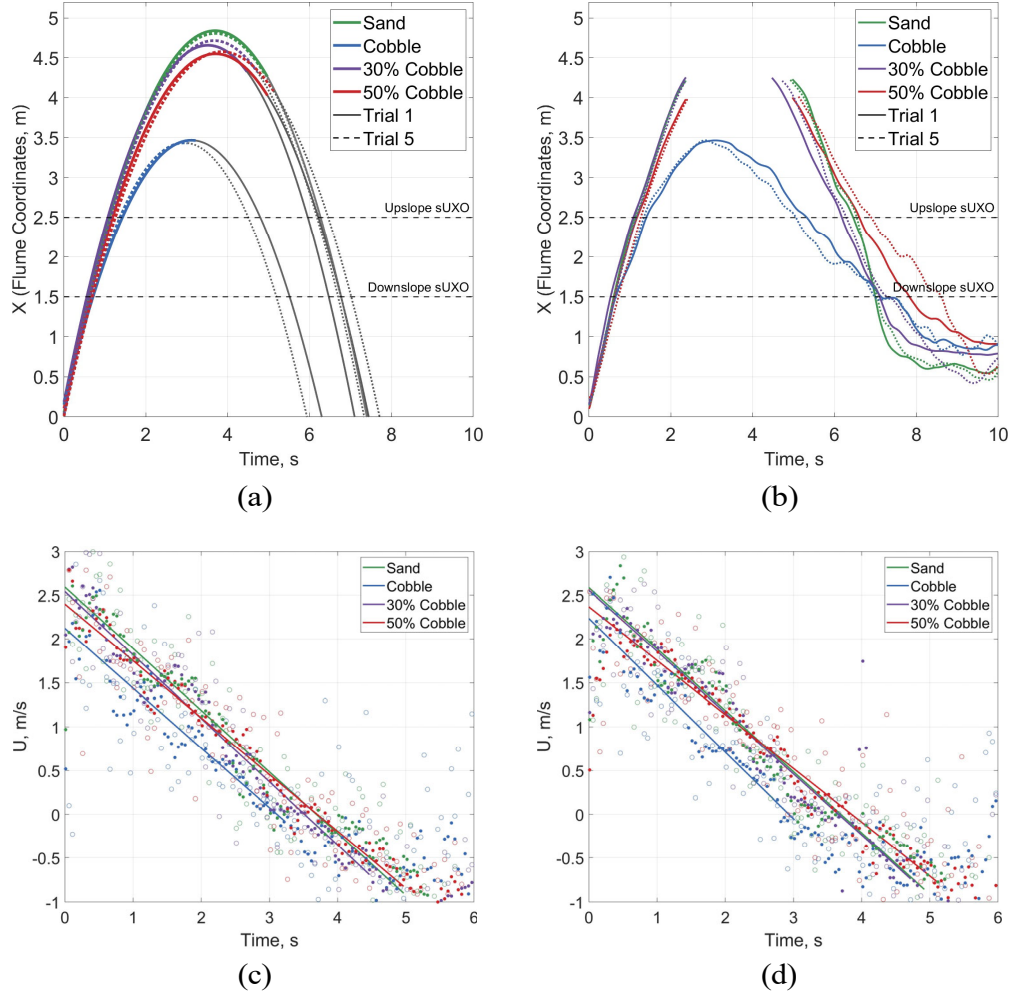


Figure 16: Trial 1 vs Trial 5 horizontal runup best fit curves (a), and ensemble averaged runup extent (b). Instantaneous bore front velocities derived from averaged runup (open circles), moving mean applied runup (filled circles), and best fit curves (solid lines).

4.1.2 Water Velocities

Two types of velocity measurements were observed and include the instantaneous bore front velocities during uprush (U_u) and the intrabore, near-bed horizontal velocities during both uprush (u_u) and backwash (u_b). The hor-

horizontal runup time series measured with the Velodyne LiDAR provided the space-time trajectory of the bore. The instantaneous velocity of the bore front during uprush was obtained by taking the derivative of the leading edge of the bore position time series. The derivative of the raw horizontal runup time series proved noisy, while the derivative of a moving mean applied to the raw time series was more easily interpreted. Overall, the smoothest estimate of bore front velocities was obtained by taking the derivative of the runup polynomial fit curve for each beach composition (Fig. 16). Maximum runup velocities during Trial 1 for the pure sand, 30% and 50% cobble beaches were approximately 2.5 m/s and occurred when the bore front reached the toe. Maximum velocities on the pure cobble beach were smaller (2.2 m/s). Maximum backwash velocities measured at 5 s after the bore reached the toe are approximately -1 m/s for all beach compositions. During Trial 5, measurements of peak velocities at $t = 0$ s cannot be differentiated from the those of Trial 1 due to measurement noise.

EMCM intrabore near-bed velocities during Trial 1 were used to estimate velocities 2 cm from the surface of the beach. True intrabore near-bed velocities may be greater than the reported velocities due to high levels of noise in the EMCM dataset. However, general magnitudes, velocity trends, duration, and flow reversal times at $X = -0.13$ m, $X = 0.47$ m, $X = 0.87$ m, $X = 1.49$ m and $X = 2.38$ m can still be deduced. Furthermore, additional Trial 1 datasets were available on the 50% and 100% cobble beach and as such, velocities are an average of 2 and 3 repeats of the initial dambreak on these two beach compositions, respectively. Peak velocities measured just before the beach toe at $X = -0.13$ m (station cart H7), approached 1.54 m/s - 1.98 m/s for all beach compositions. Maximum uprush velocities recorded at $X = 1.49$ m for the pure sand, pure cobble, 30% and 50% beach compositions were 0.8, 0.55, 0.82, and 0.89 m/s, respectively (Fig.17). Velocities at $X = 1.49$ m were assumed similar to the velocities at the downslope munition ($X = 1.5$ m) and used for inference in munition mobility in the discussion (Section 4). Flow reversal at this location and for the pure sand and mixed grain beach compositions occurred at approximately $t = 3.0$ s, which is about 1 s before the bore front was observed to have changed direction. However, flow reversal at this location on the pure cobble beach aligns with the observed bore front at approximately 3.51 s.

Intrabore near-bed velocities measured at $X = 2.38$ m were used to infer velocities closest to the upslope munition. Uprush velocities are only differentiable after $t = 2.4$ s with observable maximum values between 0.5 m/s

(50% cobble beach) and 0.95 m/s (pure sand, pure cobble, and 30% cobble beaches). Flow reversal at this location occurred 0.5 s before the observed bore front reversed direction on the mixed beach compositions and less than 1 s before the observed bore front reversed directions on the pure sand beach. Conversely, flow reversal of the intrabore near-bed velocities occurred after the observed bore front reversed direction on the pure cobble beach. Observed maximum backwash velocities on the pure sand and mixed beach compositions and at both munition locations approached 1.5 m/s. On the pure cobble beach, these velocities were smaller and varied at each munition location with velocities of approximately 1 m/s at the downslope munition and 0.22 m/s at the upslope munition.

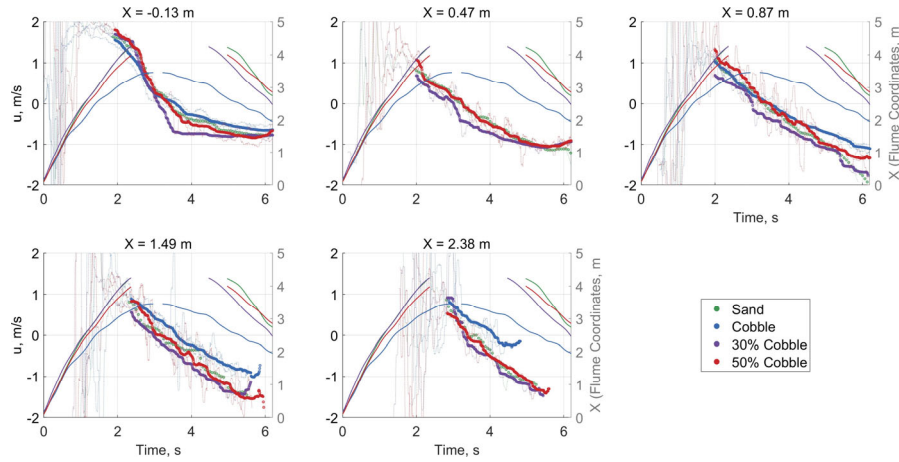


Figure 17: Intrabore near-bed water velocities at various beach locations (filled circles, left axis), aligned with associated horizontal runup (solid lines, right axis) for the Trial 1 hydrodynamic series. Beach compositions are separated by color. Unprocessed data shown in background (dotted lines).

4.1.3 Pore Pressure Gradients

Pore pressure gradients were used to infer differences in infiltration rates and are only available for the pure cobble (blue), 30% cobble (purple), and 50% cobble (red) beach compositions. Internal pore pressure data was resolved and processed from two pairs of buried pressure sensors located at $X = 1.49$ m and $X = 2.6$ m with observable maximum values at the pressure sensors deployed closest to the toe (Fig.18). At $X = 1.49$ m, maximum pore pressure gradients were approximately 0.32, with the largest observed values coming from the 50% cobble beach composition. Difference in pore pressure gradients between the pure cobble, 30% cobble and 50% cobble at $t = 2$ s (time of max observed pressure gradients for the pure cobble) were between 0.04 and 0.1, with the largest difference in pressure gradients stemming between the pure cobble and 50% cobble beach (0.1). Overall differences in pore pressure gradients between the two mixed grain beaches were small (0.06). At the upslope deployed pressure sensors, all beach composition pore pressure gradients never exceed 0.1 and remained relatively similar in amplitude with one another (± 0.03) for the duration of Trial 1.

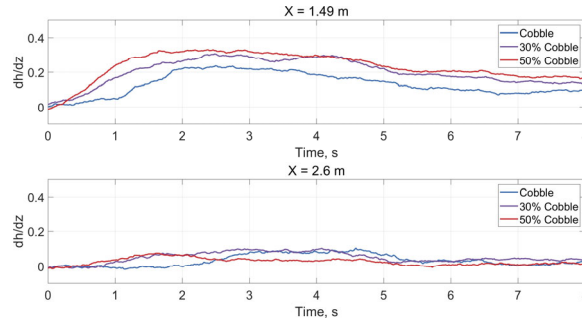
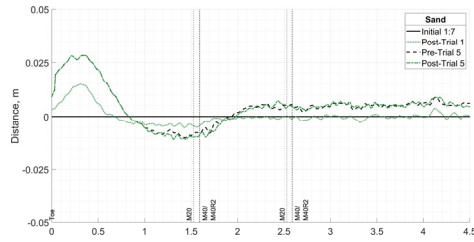


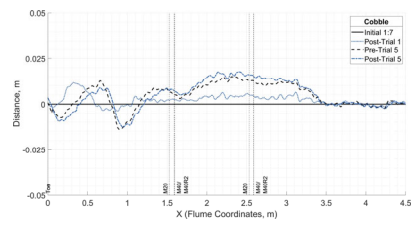
Figure 18: Internal pore pressure gradients at the $X = 1.49$ m (top) and $X = 2.6$ m (bottom) for the pure cobble (blue), 30% cobble (purple), and 50% cobble (red) beach compositions during the Trial 1 hydrodynamic series.

4.2 Morphology Observations

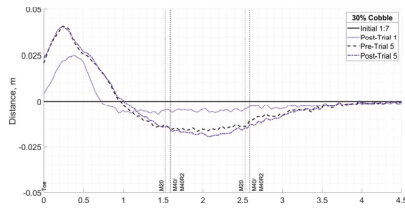
Profile development from consecutive swash events were obtained by subtracting post-trial elevation measurements of the first and fifth trials from the pre-Trial 1 measured 1:7 beach profile (Fig.19). Similar erosion and accretion patterns occurred on the pure sand and two mixed beach compositions during Trials 1-3, with offshore directed net-sediment transport. During Trial 4, accretion started to form around $X = 2$ m on the pure sand beach but reverted back to being offshore directed during Trial 5. The pure cobble beach had overall patterns of onshore directed sediment transport that settled within the boundary between the downslope and upslope munition initial deployment locations.



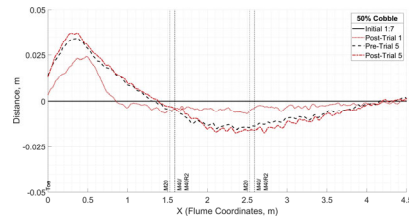
(a) Sand



(b) Cobble



(c) 30% Cobble



(d) 50% Cobble

Figure 19: Trial 1 vs Trial 5 beach profile differences. Beach compositions separated by subplot. Pre-Trial (black) and post-Trial (colored) profile differences are calculated from the initially set 1:7 (Pre-Trial 1) beach measurements are represented by line type.

4.2.1 Beach development

On the pure sand and mixed grain beaches, sediments started to accrete and form a berm near $X = 0.5$ m, $X = 0.7$ m and $X = 0.85$ m during Trial 1. In all three cases, the berm shape was negatively skewed, with the tail extending slightly offshore and beyond the toe. As trials progressed, sediments furthest upslope continued to erode, and settled downslope. The peak of the berm from the mixed beaches progressively moved towards the toe (Fig.19). Additionally, these beaches developed two peaks. The largest forming around $X = 0.25$ m and the second around $X = 0.5$ m. The sand berm did not develop as significantly as the berms from the mixed grain beaches. The location of the sand berm remained stagnant as well, and showed subtle signs of growth. A tail on the foreshore region also formed, indicating potential net-offshore sediment transport that coincided with the erosion occurring onshore of the berm. The erosion extent on the mixed beach compositions concaved the profile downward between $X = 1$ m and $X = 4$ m. The erosion extents on the pure sand beach was smaller and did not extend further onshore than $X = 2$ m. The initially set and measured 1:7 slope remained intact immediately upslope of the eroded extents for the pure sand, and mixed grain beaches.

The pure cobble beach showed signs of similar berm growth as the pure sand beach during Trial 1. However, the volume of the eroded material upslope of the berm after Trial 1 does not coincide with the volume of the berm, indicating the sediment was acquired elsewhere, or measurement errors in the Trial 1 ensemble average profile measurements exist. This issue was resolved following Trial 1, to which the berm volume reflects the eroded volume upslope. Berm migration was evident as well. After Trial 3, the peak (which was smaller than the other beach compositions) moved onshore, then reversed direction and grew slightly during Trial 5. The final location of the peak settled at $X = 0.65$ m. Additionally, the shape of the berm was positively skewed after Trial 1, then shifted to being negatively skewed after Trial 3, and remained negatively skewed for the remaining trials. The erosion extents were smaller for the pure cobble beach than the pure sand and mixed grain beaches. Erosion on the pure cobble beach did not extend further onshore than $X = 1.1$ m. Onshore directed sediment transport commonly found on pure cobble beaches was also observed during Trials 3-5 with sediments settling between $X = 1$ m and $X = 3.5$. Notably, the areas prone to erosion and accretion throughout the trials, and for all beach composition, coincided

with the downslope and upslope munition locations. As such, the difference in munition behavior between Trial 1 to Trial 5 is hypothesised to be in response to the hydrodynamic and morphology development. Similar to large cobbles or rock on a homogeneous beach, it was also assumed that some of the observed sediment transport dynamics were in response to the munitions being placed on the beach since most of the notable transport occurred at the munition locations.

4.3 Observations of sUXO Mobilization

Munition mobilization from a single swash event and consistent swash forcing (five back-to-back events) proved to be variable between munition types and by beach composition. Overall, net-horizontal migration was the smallest for all munitions and beach compositions during Trial 1. To understand the forcing mechanisms responsible for munition mobility, the initial swash event (Trial 1) is investigated first, then compared to munition migration results under multi-bore swash forcing (Trial 1 vs Trial 5).

4.3.1 Mobility during a single swash event

Results for all of the Trial 1 munition experiments on the pure cobble and mixed grain beaches are representative of the potential mobilization behavior of the munitions during a single swash event. The RealSense camera acquired observations of munition mobility throughout the swash event. Fig.20 shows the results of three series (repeated Trial 1 conditions), for each munition type (colored symbol), beach composition (colored lines), and deployment location (downslope and upslope). Tracking results (colored symbols) are overlaid on a colored horizontal runup time stack between $X = 1$ m and $X = 2.8$ m. The Trial 1 averaged horizontal runup extent captured by the Velodyne LiDAR (solid line) is overlaid on top of the horizontal runup time stack for each beach composition. Seven types of munition motion under swash bore forcing conditions were observed during this experiment (Appendix F) and include the following: no motion (X), rolling migration (herein defined as 2 cm horizontal variation between time steps (RM)), local yaw change about the nose (Y), local rotation change about the nose (R), local burial-type unknown (B), scour burial (SC), and burial from accretion (AB). Local motion refers to any angle change about the initial deployment location and no observed horizontal migration. The most common type of motion dur-

ing uprush was no motion, local yaw change, and rolling migration for all munition types, beach compositions, and munition deployment locations.

In general, the initiation of horizontal migration did not occur upon immediate impact of the bore. Instead the uprush would cause the munition yaw angle to change from being in line with the swash bore to becoming askew prior to the initiation of horizontal migration (via rolling migration). Observed yaw angles required for the munition to roll varied between the munition types and beach compositions. As such, yaw angles at the time of incipient motion were extracted from the RealSense camera measurements for series that exhibited rolling migration. At the downslope deployment location, 11 munitions exhibited rolling migration. Respective yaw angles prior to this migration ranged between (3.7 and 38 degrees). Conversely, there were only three total trials of rolling migration at the upslope deployment location. However, the incipient yaw angles were not resolvable.

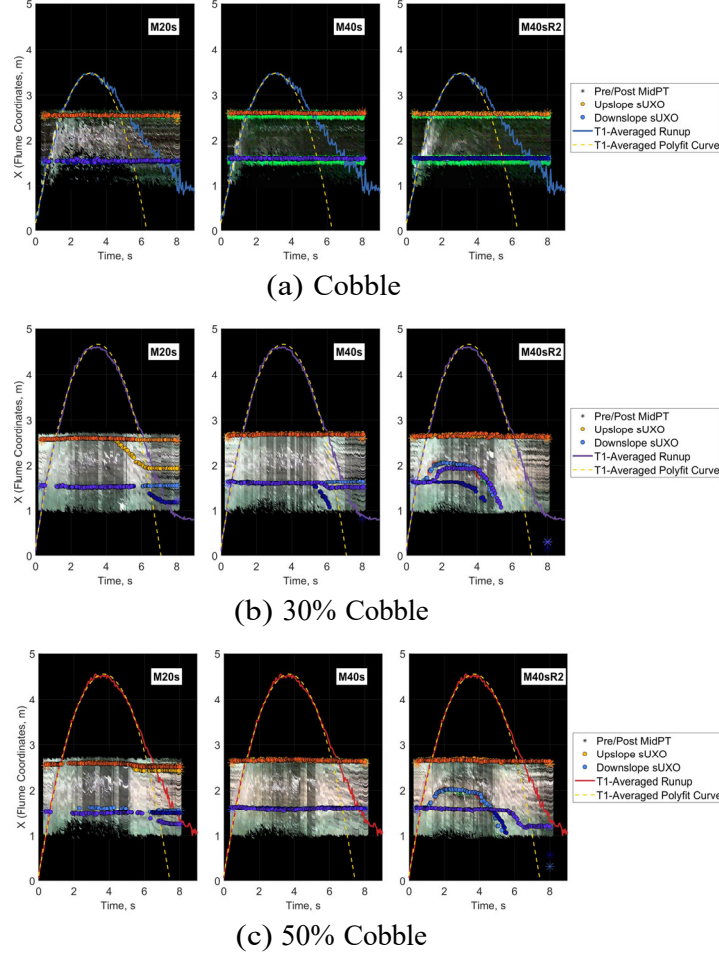


Figure 20: Munition trajectory comparison at the upslope and downslope deployment locations (filled circles) for each Trial 1 series. Background imagery is of the runup time stack from the centrally located RealSense camera that resolved the runup between $X = 1$ m and $X = 2.8$ m. Runup extent (solid line) and polynomial curve (yellow line) are overlaid on top of the time stack of the runup. Beach composition is separated by subplot row and is also indicated by color (blue, purple, or red for pure cobble, 30% cobble, and 50% cobble).

Results on the pure cobble beach showed little to no migration occurred during Trial 1 for all three munition types and at both initial deployment locations. On the 30% cobble beach, all three series involving the M40 munitions were observed to have a local yaw change during uprush to which two of the three series were observed to then horizontally migrate (via rolling migration) during the backwash period. A similar trend was observed for the M40R2 munitions on both the 30% cobble and 50% cobble beaches where uprush would induce local yaw change or rolling migration, and always resulted in offshore directed rolling migration during the backwash period. The M20 and M40 munitions on the 50% cobble beach had a range of motion that included no motion, local yaw and rotation change, burial, and rolling migration. On the mixed beach compositions, the M40R2 downslope munitions were the only munition type to follow the flow direction. Furthermore, observed offshore directed migration occurred slightly before the runup edge reversed directions. This coincides with the results from the intrabore near-bed velocities at the downslope munition to which local flow reversal was observed to occur earlier than the leading edge of the horizontal runup extent.

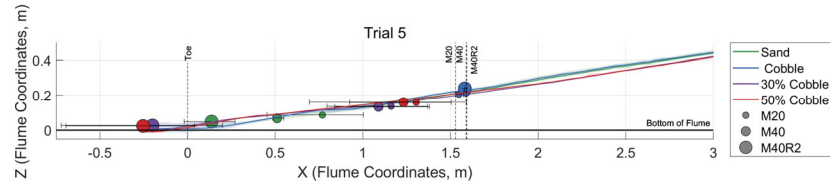
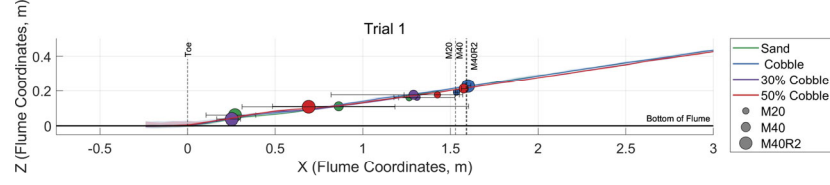
4.3.2 Mobility during consecutive swash events

Munition migration measurements of each series, taken before and after each trial of the downslope and upslope munitions were compared between Trials 1 and Trials 5. All series of the same munition type and trial number (e.g. all M20 series of Trial 1 or Trial 5) were averaged to estimate an average response for each unique munition type (i.e. series average). The series averaged munition migration results depict post-trial munition midpoint measurements (Fig.21) and the maximum migratory extents of all three series (black extents bar). Series averaged midpoint measurements are presented over an averaged post-trial beach profile (solid line). Refer to (Appendix G) for non-series averaged munition midpoint measurements.

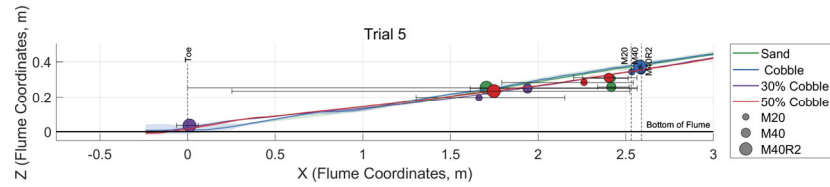
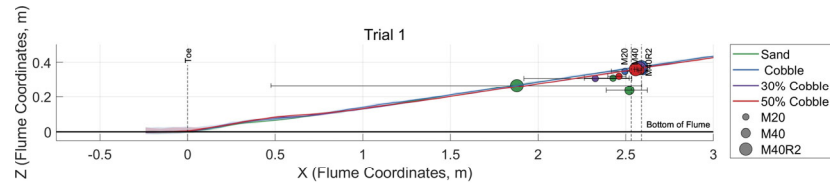
Starting with the downslope munition at $X = 1.5$ m, all munitions were either fully (M20) or partially (M40 and M40R2) buried during Trials 1 - 5 on the pure cobble beach, with very minimal net horizontal variation (< 1 cm) . Additionally, the M20 munitions were buried during uprush while the immobile M40 and M40R2 munitions showed signs of scour and scour burial around the munitions during backwash. At the downslope munition location, net horizontal migration for all munition types was offshore directed

and increased as the percent sand within the beach composition increased. As such, all munition types placed on the pure sand beach were the most mobile during Trial 1. For the pure sand and mixed grain beaches, the least dense munitions (M40R2) remained at or near the toe, proudly above the bed, during Trials 3-5. However, maximum net-horizontal migration ($X < -0.8$ m) occurred on the mixed grain beaches with the M40R2 munitions. Conversely, the most dense munitions (M20) on the pure sand beach, and the two most dense munitions (M20 and M40) on the mixed grain beaches, did not migrate beyond $X = 0.6$ m (pure sand) and $X = 1.2$ m (mixed grain) after five swash events. Independent of initial munition deployment location, sediments scoured around immobilized munitions during backwash on the pure sand and mixed grain beach compositions.

Munition mobility varied significantly between the series of the same munition type and beach composition after only 1 swash bore interaction. Munition response for the upslope munition (less energetic swash location) was motionless on the pure cobble beach, and all munition types were either partially or fully buried in place after five swash events (Fig.21). The least dense munitions (M40R2) had the largest net-horizontal migration and migrated downslope the greatest distance during Trial 1 on the pure sand beach, and during Trial 5 on the 30% cobble beach. Burial at the upslope munition location on all beach compositions was observed after Trial 1 for all munition types. The M20 munitions and M40 munitions had the most significant burial on the 50% cobble beach. Note, vertical measurements for the upslope munitions sand experiments were unreliable. As such, migration should only be reviewed with respect to horizontal migration and any observations of munition burial at this location are ignored.



(a) Downslope Munition



(b) Upslope Munition

Figure 21: Series averaged munition horizontal migration after Trial 1 (a) and Trail 5 (b) at the downslope and upslope munition initial deployment locations. Series variability of the same munition type and trial number are indicated by the black extent bars. Beach composition is indicated by color and munition type by symbol size. Munition measurements are plotted over the averaged post-trial beach profiles for the pure sand (green), pure cobble (blue), 30% cobble (purple), and 50% cobble (red) beach compositions.

4.4 NHWAVE Hydrodynamic Results

Numerical simulations were attempted using 10, 15, 20, and 25 vertical layers to find representative calibration parameters to the 50% cobble beach. Initial reservoir depths in the model were set to 58 cm to represent laboratory experimental conditions. As such, Trial 1 observed water depths at the downslope ($X = 1.5$ m) and upslope ($X = 2.5$ m) munition initial deployment locations and horizontal runup extent on the 50% cobble beach were compared to the result from the different numerical simulation runs with varying vertical layer. The orange line is our control simulation with no bottom friction or viscosity, and the blue line the laboratory observations for the 50% cobble beach (Fig.22). In this case, 20 vertical layers were found to be an optimal compromise between accuracy and computational effort. To avoid unreasonably small-time steps when using 20 vertical layers, the horizontal resolution was reduced from 1 cm to 2 cm. No significant divergence in the results were observed. Water depths were matched with the 50% cobble beach laboratory observations to within a few centimeters at the downslope and the upslope munition initial deployment locations.

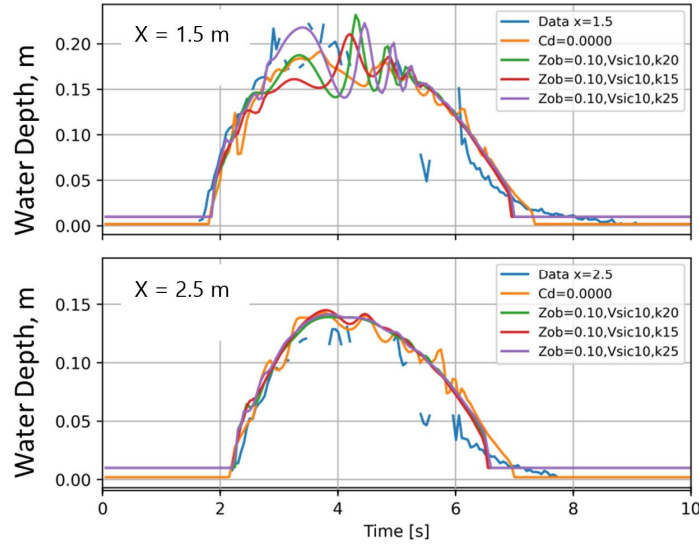


Figure 22: Water depth from laboratory Trial 1 experiments for the 50% cobble beach composition (blue), modeled with 15 vertical layers (orange), and modeled with 25 vertical layers (green) at the downslope ($X=1.5$ m) and upslope ($X=2.5$ m) munition initial deployment locations. All simulations are viscous with bottom roughness according to the median grain size. Model run time (Time, s) indicates the time since dambreak.

4.4.1 Dambreak Swash Vulnerability to Changes in Slope & Initial Bore Energy

In using the representative calibration parameters from the 50% cobble beach set to a 1:7 (8.0°) slope (faded purple circles), intrabore near-bed water velocities 2 cm above the bed and corresponding water depths were extracted from the simulation results. Results comparing the velocities and water depths of the calibrated 50% cobble beach (8° slope) at the downslope munition align closest to the laboratory observations of the 50% cobble beach (red circles) during uprush (Fig.23) and overestimate water depths experience for the same magnitude backwash velocities. The calibrated 50% cobble beach (8° slope) maximum backwash velocity was approximately 0.5 m/s larger than laboratory observations for the 50% cobble beach.

At the upslope munition, the calibrated 50% cobble beach (8° slope) over predicted the water depths during uprush and backwash. The stan-

standard deviation between observed measurements and modeled water depths was (± 0.007) during uprush with water velocities between $u_u = 0.61$ m/s and $u_u = 0.71$ m/s. After flow reversal, the difference between observed measurements and modeled water depths increased. At $u_b = -1.4$ m/s, the standard deviation between observed measurements and modeled water depths were ± 0.05 m.

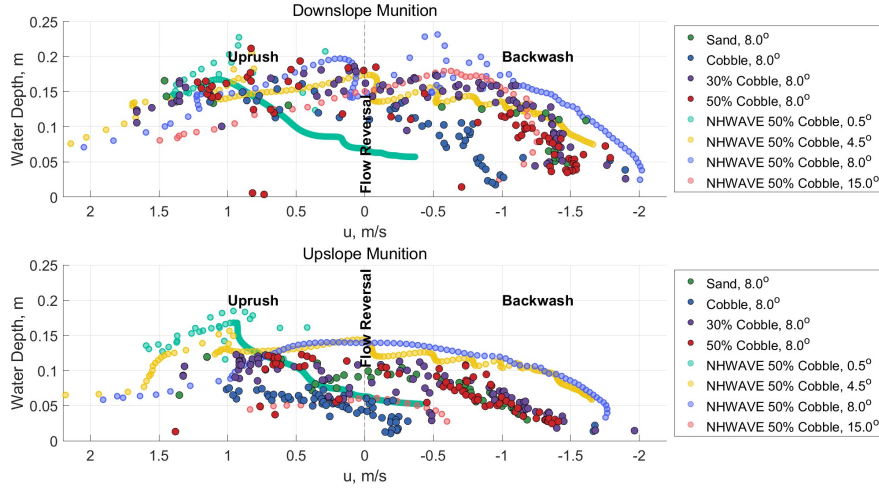


Figure 23: Comparison of laboratory observations and NHWAVE numerical simulations. Shown are the Trial 1 intrabore near-bed water velocities 2 cm above the bed versus water depth for all laboratory beach compositions at the downslope (top) and upslope (bottom) munition initial deployment locations. Observed measurements are compared to NHWAVE numerical simulations of the calibrated 50% cobble beach with varied beach slopes (0.5° , 4.5° , 8° , and 15°). Beach compositions and simulation with altered beach slopes are denoted by color in the legend. Intrabore near-bed water velocities are separated into uprush (left) and backwash (right) of the flow reversal time ($u = 0$ m/s.)

Beach state was investigated next through simulations using the same parameters used for the calibrated 50% cobble beach but with variable mild to steep beach slopes (0.5° , 4.5° , 8.0° , and 15°). Trial 1 water depth measurements for the pure sand (green circles), and 30% cobble (purple circles) beach compositions from laboratory experiments (8° slope) resembled the water depths from the simulated 50% cobble beaches with the 4.5° and 8.0° intermediate beach slopes. Maximum uprush velocities on the intermediate beach slopes never exceeded 2.2 m/s and -2.0 m/s during backwash, at the downslope munition. At the upslope munition, uprush velocities on the intermediate beaches remained at 2.2 m/s and reduced by about 0.3 m/s – 0.4 m/s during backwash.

The calibrated 50% cobble beach results with 0.5° and 15° slopes resemble the water depths and backwash velocities observed on the pure cobble

beach (blue circles) at the upslope munition but does not resemble the laboratory pure cobble beach measurements at the downslope munition. Instead, the calibrated 50% cobble beach with a 15.0° beach slope has smaller water depths, by about half, than the other slope simulations and beach compositions. Water depths for the calibrated 50% cobble beach with a 15.0° slope align within a few centimeters of the observed water depths for the 30% cobble beach during backwash. Meanwhile, the calibrated 50% cobble beach with 0.5° slope has the largest water depths (approximately 0.23 m) when compared to all other laboratory observations and simulations during uprush. The calibrated 50% cobble beach with 4.5° slope has similar velocities and water depths as the pure sand, 30% cobble and 50% cobble beach compositions when uprush water velocities are greater than 0.7 m/s.

Variable swash energies were also explored through numerical simulation using the calibrated 50% cobble beach parameters and 8.0° slope. Five initial reservoir depths were attempted and include 33 cm, 38 cm, 43 cm, 48 cm, and 53 cm. The intrabore near-bed water velocities 2 cm above the bed and corresponding water depths from these energy simulations are compared to the results of the calibrated 50% cobble beach simulation with a 58 cm initial reservoir depth and the Trial 1 observations from laboratory experiments conducted on the 50% cobble beach (Fig.24). In reducing the initial reservoir depth, the swash bore energy is decreased, resulting in smaller water velocities and water depths. Uprush water depths and velocities for numerical simulations using initial reservoir depths set to 58 cm most closely align with laboratory 50% cobble beach observations at the downslope munition and upslope munition initial deployment locations. Conversely, backwash water depths and velocities for numerical simulations using initial reservoir depths set to 43 cm and 48 cm better represent laboratory 50% cobble beach observations at the downslope munition and upslope munition locations

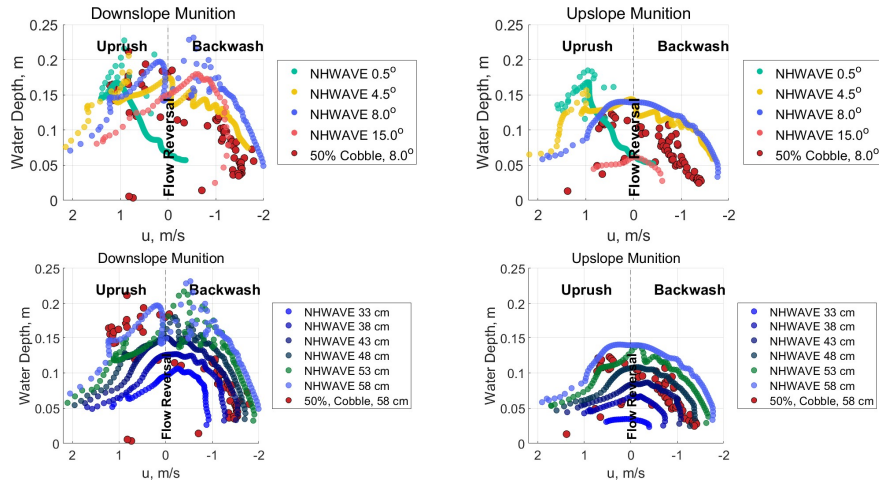


Figure 24: NHWAVE modeled water velocities vs water depth for simulations of altered slope and varied initial bore energy. Intrabore near-bed water velocities 2 cm above the bed versus water depth at the downslope ($X = 1.5$ m) and upslope ($X = 2.5$ m) initial munition deployment locations. The bottom rows show the calibrated 50% cobble beach set to a 8° slope and varied initial bore energy (i.e. reservoir depth). Simulated dambreak energy conditions were altered by increasing the simulated reservoir heights from 33 cm to the laboratory condition of 58 cm. All simulations (slope and bore energy) are compared to the Trial 1 observed measurements for the 50% cobble beach composition (red circles). All simulations are denoted by color in the legend. Intrabore near-bed water velocities are separated into uprush (left) and backwash (right) of the flow reversal time ($u = 0$ m/s.)

5 Discussion

5.1 Hydrodynamic and Morphodynamic Response

Results show that there are at least five observable hydrodynamic and morphodynamic mechanisms that can induce net-offshore directed sediment transport, erosion of the beach face, and increase the maximum horizontal runup extent: 1) a decrease in infiltration during uprush, 2) larger overall water depths throughout the swash event, 3) reduced shear stresses, bed roughness and bed friction 4) reduction in the asymmetry of the swash trajectory, 5) shallowing of the beach profile. To understand the way these processes facilitate the appropriate conditions for erosion of bed material to occur, a comparison between the four beach compositions should be considered.

Porosity is defined as the percentage of void (empty) space within a material such as rocks, soil, or media, and is calculated as the fraction of volume of void space over the total volume. Permeability is the ability of fluid to flow through porous media. Beaches with high permeability are typically comprised of large grain sediments and have higher infiltration rates than beaches comprised of finer grain sediments with low permeability. When the swash bore impacts the beach face, the beach water content increases due to infiltration during uprush, and drains during backwash. The sediment grain size and void space will determine the speed at which the swash bore infiltrates the beach face. The pure sand beach is a low porosity and permeability beach with slower infiltration rates than could be expected on the pure cobble beach with a median grain size 60 times as large. Results for the maximum horizontal runup extent was the largest for the pure sand beach and the smallest for the pure cobble beach; suggesting infiltration rates were slowest on the sand beach due to the fine grain sediment and allowed the runup extent to reach the furthest landward position when compared to the runup extents of the other three beach compositions. Results show overall erosion and net-offshore directed sediment transport occurred over the course of 5 trials for the pure sand beach. Maximum water depths throughout the swash event was also observed for the sand beach and 30% cobble beach. The combination of low infiltration rates and larger water depths might have induced suspension of the sediments during uprush. The sediment grain, being smaller and lower in density, would not have settled by the time of flow reversal, and as a result, the faster backwash velocities observed on these two beaches would mobilize the suspended sediment offshore. Furthermore, pore

pressure gradient results at $X = 1.49$ m were not observed to be significantly different between the 30% cobble and 50% cobble beach compositions, implying the infiltration rates could be similar on the two mixed grain beach compositions. As such, the increase in bed roughness values from a pure sand, 30% cobble, and 50% cobble beach compositions might be a controlling factor for reducing horizontal runup extent and sediment transport, more than infiltration alone. However, pressure sensor data is not available for the pure sand composition. For an accurate analysis that determines the dominant process, infiltration or bed roughness, of the frictional force acting on an object, pore pressure gradients and hydraulic conductivity at several horizontal locations and elevations within the four beach compositions would be required.

Bed roughness values and corresponding friction can reduce the magnitude of the runup, as well as the overall duration of each swash event. Frictional effects have also been observed to increase the total swash trajectory more significantly on shallower beach slopes. As such, reduced horizontal runup extent and reduced water velocities for the mixed grain beach compositions could also be the result of the increased bed roughness and bed friction due to the bimodal sediment grain mixture in each beach face. It is also common for mixed beaches to naturally redistribute smaller sediments downslope and larger upslope. The homogeneously mixed beach began to self sort as trials progressed. A large portion of the cobble became proud on the surface of the profile, and gathered near the toe, and the sand settled within the voids of the beach. Eventually, the beach profile became non-homogeneously mixed altering the bed roughness and permeability enough to reduce bore front velocities as the trials progressed. In the case of the self-sorted mixed beaches observed in this study, the relative bed roughness can be decomposed into two layers. Underneath would be the less permeable beach surface with smaller infiltration rates, porosity values, and bed roughness due to the settling of the grains within the voids. On top would be the remaining loose sediment and cobbles, likely protruding outward into the swash flow, and becoming more susceptible to the mobilizing forces that induce motion and sediment transport. For instance, large cobbles on a sand bed have been observed to migrate shoreward while suspended above the bed during uprush. Prior to or upon flow reversal, the object would settle back on top of the bed, and migrate offshore during backwash; this time moving downslope by sliding over the top of the finer bed sediments.

Asymmetry of the swash trajectory is a conjoining explanation for the

offshore-directed sediment transport on the pure sand and mixed grain beach compositions. Under ideal conditions, the swash tip trajectory of an incompressible, inviscid fluid, over a reflective beach will be perfectly symmetry and parabolic in shape. An approximate calculation for the horizontal runup extent can therefore be modeled as a particle moving upward under the influence of gravity and friction alone, also known as the ballistic solution (Svendsen, 2006). As deviations from this ideal solution are introduced to the system such as diffusive beach properties from infiltration, and added frictional and bed roughness values, asymmetry of the swash trajectory is created. In this study, asymmetry of the trajectory increased as the percent of sand in the beach mixture decreased. The decrease in asymmetry coincides with faster instantaneous bore front velocities and intrabore near-bed velocities observed during backwash, especially at the upslope locations near $X = 1.49$ m and $X = 2.39$ m. For the pure sand beach composition, the trajectory of the swash is nearly symmetrical, coinciding with uprush intrabore near-bed velocities nearly equivalent to the pure cobble beach at $X = 1.5$ m but approximately 1.7 times greater than the cobble beach during backwash. Despite the increased asymmetry of swash trajectory on the 30% and 50% cobble beaches, intrabore near-bed backwash velocities at $X = 1.5$ m were not significantly different than the velocities of the pure sand beach. However, both beaches did have the greatest erosion and profile change during the five swash events.

Changes in beach slope can significantly affect sediment mobility. As beach slope steepens, the restorative forces on the sediment particle or object will decrease, and mobilizing forces will dominate and induce motion. Morphological progression of the beach profile over the course of five swash events did show a subtle steepening in the beach face for the pure cobble and pure sand beaches. The mixed cobble beach profiles flattened upslope of $X = 0.5$ m but a steep slope offshore of this location developed as trials progressed. The intermediate beach state of the mixed beach compositions is difficult to understand through observation alone. As such, we revert to sediment transport theory to estimate the mobilizing forces required to induce sediment motion by calculating the Shields parameter for each unique beach composition.

5.2 sUXO Response

Munition mobilization and burial results from the double-dambreak laboratory experiment under swash bore forcing conditions showed that munitions deployed initially proud with the nose to tail aligned parallel with the direction of the propagating bore can be mobilized. Munition horizontal migration and burial varied by munition type (M20, M40, and M40R2) and by beach composition (pure sand, pure cobble, 30% cobble and 50% cobble). Horizontal migration data was captured in two ways, 1) via manual measurements of the nose and tail pre- and post- trials and 2) using three RealSense cameras positioned over the flume, face down to capture munition motion in real time, through which incipient motion could be observed. Munitions initially deployed downslope ($X = 1.5$ m) generally experienced the most net-offshore migration after Trial 1 whereas munitions initially deployed upslope ($X = 2.5$ m) required more than one swash event to migrate more than 0.5 m downslope of their initial deployment location. Aside from the M40R2 munitions on the 30% cobble beach, munitions did not migrate further downslope than $X = 1.6$ m. Notably, the areas prone to erosion and accretion throughout the trials, and for all beach compositions, coincide with the downslope and upslope munition locations. As such, the difference in munition behavior between Trial 1 to Trial 5 is hypothesised to be in response to the hydrodynamic and morphology change as trials progressed.

The two densest munitions (M20 and M40) were not observed to migrate onshore at any part of the swash event. For the least dense munitions (M40R2) that were initially deployed downslope, horizontal migration mimicked the direction of the swash flows following incipient motion such that the munitions moved slightly onshore during uprush with most of the migration occurring with the backwash flows downslope. The net-horizontal munition migration at both downslope and upslope deployment locations was offshore directed. A relationship between density and distance traveled was observed for the pure sand, and two mixed beach compositions such that the densest munitions (M20) migrate the least or bury, and the least dense munitions (M40R2) migrate the farthest downslope for Trials 1 - 5. Conversely, during the cobble case, all munition types and at both initial deployment locations, were not observed to migrate (< 2 cm). Of note, the M40R2 (least dense munition) was covered by rough knobs, that acted as bio-foul for a different, yet concurrent project. Likely the roughness of the munition caused it to slow its mobility, while the low density enhanced mobility. In future experiments,

we would likely not use the same munition type for the low density munition case. Additionally, we would likely have three munitions of the same size to test the influence of density, and then several munitions of different size, but same density to test the influence of size.

The bed roughness on the pure cobble beach likely played a more critical role in preventing munition mobility than on the other beach. Other factors such as shallower water depths (Fig. 14) on the cobble beach could also explain why the M40 and M40R2 munitions did not migrate, despite protruding further into the direct line of the swash flow. Bed roughness was likely to have influenced munition mobility on the mixed beach compositions as well, especially for the densest munitions (M20) since these migrated the least downslope overall, but also for the middle density munitions (M40) which took several swash interactions to migrate downslope. Note, burial and horizontal migration could vary significantly between the series of the same munition type and beach composition. This is likely the result of leaving the munitions in place after each trial which, beyond the initial trials, leaves the munitions to experience variable and incompatible swash bore energies as the trials progress and munitions continue to migrate.

Lastly, munition burial occurred most frequently during backwash. For the pure cobble cases, morphological burial was observed through the displacement of cobble during the uprush that settled atop the stationary munitions (specifically the M20 munitions). The bore loses energy on the pure cobble beach composition (energy dissipation) and does not have the same backwash velocities as uprush velocities. As such, the swash deposits the sediment on top of the profile (upslope) during uprush and due to the loss in energy, can not re-mobilize the sediments enough to bring them back down slope. Instead the sediments settle on, or around the munitions, slowly burying them in place. Conversely, scour burial was observed for immobile munitions throughout the swash event or once mobilized munitions stopped moving on the pure sand and mixed grain beach compositions. Scour formation is correlated to the increase in turbulence caused by an object (or munition) obstructing the flow regime. The turbulence increases the shear velocities around the munition perimeter, resulting in the mobilization and transport of sediment elsewhere. This creates a scour hole that the munitions settle within.

5.2.1 Slope corrected object mobility number

The object mobility number is a version of the Shields parameter; however it is used to estimate mobility threshold conditions for an object such as the munitions in the nearshore and is described as

$$\Theta_m = \frac{U^2}{\left(\frac{\rho}{\rho_m} - 1\right) g D_m}, \quad (3)$$

where Θ_m is the object mobility number, U is water velocity, ρ_m is the density of the munition, and D_m is the munition diameter. The $\rho * U^2$ in the numerator is used to approximate the shear imposed on the munition in the object mobility number. For objects and munitions much larger than the surrounding bed roughness, k_s , the amount that the object is protruding out into the flow will increase, thereby making the object more susceptible to mobilizing conditions and behavior (via pivoting, sliding, or rolling). Conversely, smaller objects (and munitions) might lie within the wave boundary layer or sink further within the pockets of the bed material. The slope correction term, η , is also applied to the object mobility number to account for the munitions mobility due to gravity on a sloping beach. The slope corrected object mobility number (θ_{mSC}) is then described as θ_m/η . Critical shear stress values will decrease for objects with relative grain diameters larger than the length scale of the bed roughness ($D/k_s > 1$) and increase as this ratio gets closer to or below 1 (Wiberg and Smith, 1987). In this case, the ratio between the diameter of the M20, M40, and M40R2 munitions and the bed roughness were all greater than 1 for the four beach compositions. As such, the object mobility numbers were calculated under the assumption that the friction coefficient ($\tan\alpha$) in the slope correction term (η) were negligible and set to 1 (Fig.25).

5.2.2 Overall Munition Mobility

Previous investigations have compared KC , θ , and the total distance traveled by the munition to the object mobility number (Rennie et al., 2017; Cristaudo and Puleo, 2020). The current experiment observed the effect of single swash events with the aim to investigate the relationships between the slope corrected object mobility number θ_{mSC} to munition migration and other hydrodynamic swash characteristics (water velocity and water depth).

The object mobility number was calculated using the intrabore near-bed velocities measured 2 cm above the bed for each beach composition during Trial 1 hydrodynamic experiments. However, the uprush water velocities were only resolved after 2.5 seconds from the time the bore first reached $X = 0$, which means a large portion of the uprush velocities were missed, and from previous experiments using the dambreak generated swash bore, we expect the maximum uprush velocities to be closer to 2 m/s. As such, the maximum uprush intrabore near-bed water velocities from the 50% cobble beach were used for calculations on the 30% cobble beach since these velocities after processing came out to be the larger velocities between the two mixed grain beaches. Calculated slope corrected object mobility numbers are compared to the series-averaged total migration distance, D_x , observed during the Trial 1 dambreak experiments (Fig.25) for three munition types and four beach compositions. Results are separated by uprush (left of zero) and backwash (right of zero) and for upslope and downslope directed migration.

The maximum slope corrected object mobility number was 2.41 for the downslope M40R2 munition on the 50% cobble beach during backwash. There was an approximate 95% difference in θ_{mSC} for munitions deployed downslope on the pure cobble beach composition compared to munitions deployed downslope on the pure sand and mixed cobble beach compositions. Minimum θ_{mSC} values occurred during backwash on the pure cobble beach composition and at the upslope initial deployment location with $\theta_{mSC} < 0.04$ for all munition type. At both initial deployment locations and for the four beach compositions, θ_{mSC} values are the largest for the least dense munitions (M40R2) and the smallest for the middle density munitions (M40) during uprush and backwash. There is no apparent difference between the object mobility numbers calculated with or without the slope corrected term, η , potentially since all slope corrected calculations used a friction coefficient equal to 1.

No relationship could be made between the slope corrected object mobility numbers and the distance traveled during uprush and backwash for this experiment. The M40R2 munitions were the only munitions observed to migrate upslope during uprush while all other munitions migrated solely during the backwash. Interestingly, migration distances of the same munition type varied under the same flow conditions (and object mobility numbers). The variability in munition migration distances between the series is presented as extent bars from the symbol in Fig.25 and occurred predominately for the M40 and M40R2 munitions initially deployed downslope within the higher

energy swash conditions. The variability could be due to small temporal and spacial hydrodynamic and pore pressure effects not accounted for in this endeavor. Future investigations could also benefit by incorporating variable initial munition orientations and determine the threshold munition nose angle required prior to incipient horizontal migration (roll). In addition to θ_{mSC} , identifying the critical object mobility number of munitions deployed on the pure cobble and mixed beach compositions was attempted.

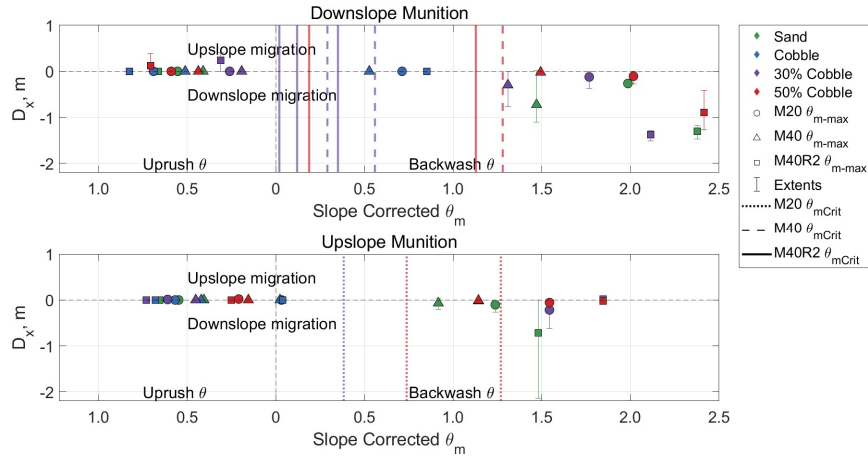


Figure 25: Slope corrected object mobility number calculated with maximum intrabore near-bed water velocities for each beach composition. Incipient motion was observed for three M40 munitions (dashed lines) and five M40R2 munitions (solid lines) at the downslope initial deployment location and three M20 munitions (dotted lines) cases of incipient motion were observed at the upslope initial deployment location. Critical object mobility numbers at time of incipient motion are denoted as vertical lines.

5.2.3 Munition Incipient Motion

Of the 36 Trial 1 series, presented in Fig.25), five instances of M40R2 incipient motion cases, and three instances of M40 incipient motions cases could be captured for munitions initially deployed downslope. For upslope initially deployed munitions, 3 instances of M20 incipient motions cases were observed. Note, more than 11 munitions migrated during the initial trials. However, incipient motion was not visible when munitions were completely submerged

by the water and as such, all incipient motion cases were only captured during backwash when the initial turbulence of the bore had reduced, and the water had cleared enough to make the munitions visible again. Munition experiments on the pure sand beach composition are also not available since the RealSense cameras were not deployed during those iterations of laboratory experiments.

Using the time of incipient motion to determine the critical water velocities, the critical object mobility parameters, θ_{mcrit} were estimated. These values are representative of the critical object mobility numbers required for the initiation of munition horizontal migration. The dotted, dashed, or solid lines characterize the munition type (M20, M40, and M40R2 respectively) for the 11 captured incipient motion cases (Fig.25). The M40R2 munitions had the smallest θ_{mSC} values and ranged between 0.02 and 0.35 on the 30% cobble beach. The largest M40R2 θ_{mcrit} value on the 50% cobble beach was 1.13 and was 6 times the second observed θ_{mcrit} value (0.19). The M20 munition were the only munitions for which incipient motion could be deduced. The smallest θ_{mcrit} for the M20 at the upslope location is 0.38 and occurred on the 30% cobble beach and maximum θ_{mcrit} were as large as 1.26 on the 50% cobble beach. It appears that as the percentage of cobble increase, critical object mobility numbers increase. Furthermore, smaller intrabore near-bed backwash velocities were able to initiate motion than maximum velocities measured. This relationship shows how the increase in bed roughness increases θ_{mcrit} values, independent of munition density and size.

Fig.26 depicts the slope corrected object mobility numbers with respect to their corresponding intrabore near-bed water velocities during uprush and backwash. Dotted, dashed, and solid black lines depict all possible θ_{mSC} values for those specific munition size and densities under the velocities observed in this experiment (approximately -2 m/s to 2 m/s). Munition type is represented by symbol and beach composition by color. The purpose of this figure is to show the correlation in critical object mobility number and velocity. If all three Trial 1 series of the same munition type did not migrate, maximum object mobility numbers are plotted instead. An "X" through the symbol denotes three series where no migration was observed during the Trial 1 experiments. Munition trials that did have measured and observed migration but the incipient motion was not captured are not included in this analysis. Starting with the M40 munitions, near-bed velocities do not appear to reach the critical velocity required for incipient motion during backwash on the 30% and 50% cobble beach compositions and thus, no motion was observed. Con-

versely, the M40R2 munitions did migrate during uprush (not shown) and maximum θ_{mSC} values on the mixed grain beach composition were less than 0.7, implying the mobilizing forces during uprush were slightly larger than those required to mobilize the munition during the backwash ($\theta_{mcrit} < 0.35$) on the 30% cobble beach.

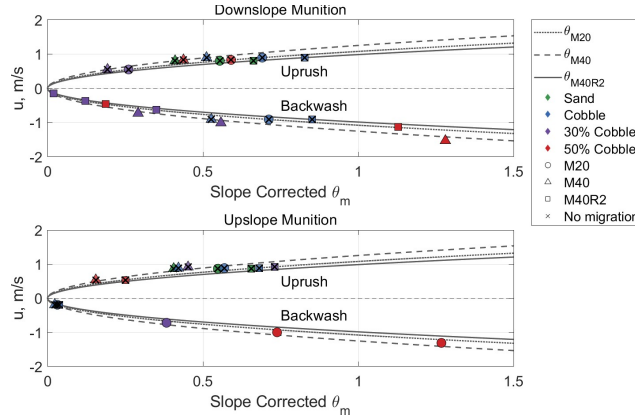


Figure 26: Slope corrected critical object mobility number calculated with the critical intrabore near-bed velocity observed at time of munition incipient motion for each beach composition. Observations of incipient motion during uprush and backwash are plotted separately. Maximum object mobility numbers calculated with maximum intrabore near-bed velocities are plotted for munitions that did not show any horizontal migration for all three series during Trial 1.

The critical object mobility numbers (θ_{mcrit}) can be coupled with the calibrated NHWAVE modeled simulations to determine the influence of slope and onset flow velocities on munition incipient motion. As such, the interpolated intrabore near-bed backwash water velocities (u_b) are used to solve for a variety of object mobility numbers across various beach slopes ranging between 0° and 35° . The matrix of object mobility numbers were solved twice, once to investigate the M20 munitions and again with the M40 munitions. Results are shown as a colored plot of u_b for all observed backwash velocities versus possible beach slopes, β (Fig.27). All available critical mobility numbers were averaged for the same munition type (M20, M40, or M40R2) and same beach composition (30% cobble or 50% cobble). Munitions did not mobilize on the pure cobble beach composition, and sand experiments do not

have incipient motion θ_{crit} results. Therefore, these two beach composition are omitted from the comparison. Averages of the θ_{crit} values are shown as contour curves and represent the conducive environments for object mobility. Munition types are represented by line style (dotted, dashed, and solid) with respective beach composition indicated by color (purple or red).

The next goal was to find a way to merge the laboratory and experimental results together in a way that allowed us to predict the environmental conditions conducive for munition mobility. TO do this, the maximum velocities extracted 2 cm above the bed that the numerical simulations produced during backwash are used to solve the object mobility number for the M20 and M40 munitions. The solutions to the object mobility number for each of the simulations are show on Fig. 27 as a different symbol type. In the legend, RH refers to the reservoir height simulations that changed the initial water depth and while the beach slope remained at 1/7 (8.0°). Results are plotted for the downslope and upslope munition initial deployment locations. Points to the right of these incipient motion curves are predicted beach state and hydrodynamic forcing expected to mobilize munitions (motion), while to the left, munitions are expected to remain immobile (no motion).

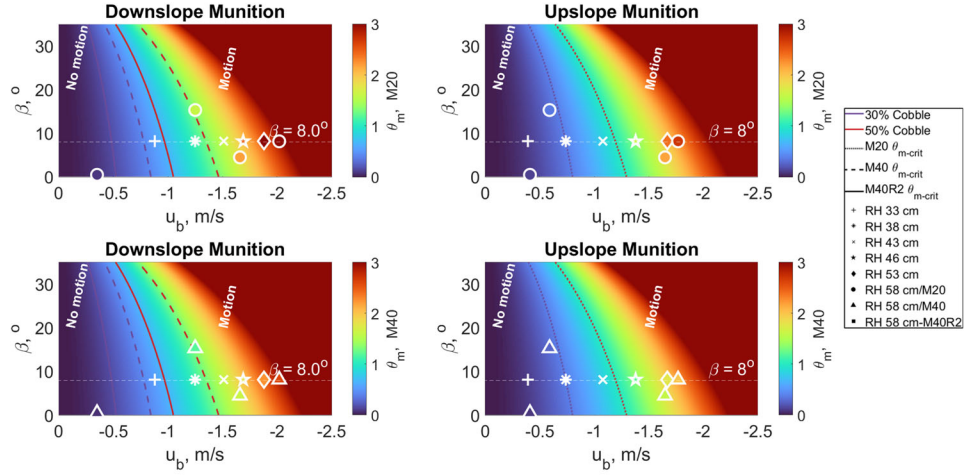


Figure 27: Threshold for initiation of munition motion as a function of intrabore near-bed water velocities and beach slope. Slope corrected object mobility numbers calculated for all observed intrabore near-bed velocities and beach slopes ranging between 0 and 30°. Calculations using the M20 munition diameter (20 mm) are shown in the first row and calculations using the M40 munition diameter (40 mm) are shown in the second row. Thresholds for initiation of motion curves are calculated from the critical objected mobility numbers of the M20 (dotted lines), M40 (dashed lines), and M40R2 (solid lines) incipient motion cases observed during Trial 1 on the 30% cobble and 50% cobble bed and at the downslope (M40 and M40R2 observed) and upslope (M20 incipient motion observed) munition initial deployment locations. Slope corrected object mobility numbers are calculated from the simulation results for the M20 and M40 munition diameters. Simulation parameters are represented by symbol and respective beach slope on the y-axis. The abbreviation “RH” in the legend refers to reservoir height used for the NHWAVE simulation.

According to the threshold mobility figure, M20 munitions will mobilize on a 50% cobble beach (red dotted line) for intrabore near-bed backwash water velocities greater than -1.3 m/s on a very mild to nearly flat beach and for backwash water velocities greater than -1.16 m/s and beach slopes greater than 8.0°. Alternatively, munitions are not expected to mobilize on 50% cobble beaches with a $\beta = 15.0^\circ$ since water velocities will not exceed the necessary backwash critical velocity values. Based on the results of the

simulations that altered the initial reservoir heights, munitions deployed at $X = 2.5$ m will not mobilize for dambreak generated swash produced from initial reservoir depths less than 48 cm and for corresponding water velocities less than 1.38 m/s. The larger M40 munitions were investigated at the downslope initial deployment location. The threshold for incipient motion on the 50% cobble beach for the M40 munition (red dashed line) for shallow sloping beaches and velocities greater than 1.45 m/s. As beach slope steepens, the critical velocities required to induce motion decrease. Furthermore, the maximum backwash velocities generated from a 15.0° beach slope and 58 cm reservoir height would likely cause M40 munitions to mobilize if deployed at $X = 1.5$ m. This is also true for munitions placed on a 8.0° beach slope with initial reservoir depths greater than 43 cm (1.51 m/s).

6 Conclusion

The addition of bimodal sediment mixtures to the beach composition complicates the hydrodynamic swash processes, and sediment transport mechanics of a beach. The presence of either a shallow or steep beach slope under swash forcing conditions can also lead to an increased probability for munition mobility to occur. As such, the investigation and analysis of munition mobility in this study span a range of beach compositions from purely homogeneous (sand or cobble), to mixed grain beach compositions of varying sand/cobble ratios (70% sand / 30% cobble or 50% sand / 50% cobble). Three surrogate munition types (M20, M40, and M40R2) of variable densities (7999 kg/m^3 , 5720 kg/m^3 , and 2460 kg/m^3) and diameters (2 cm, 4 cm, and 9 cm) were tested under repeated single swash forcing conditions conducted in a double-dambreak wave flume at the University of Delaware. Two munitions of the same type (size and density) were initially deployed at a downslope ($X = 1.5 \text{ m}$) and upslope ($X = 2.5 \text{ m}$) beach location to assess munition mobility at variable swash energies and water depths.

Depending on the beach composition and munition initial deployment location, the dam-break generated swash would generally initiate motion on the backwash of the bore. Backwash induced incipient motion was observed for 11 different munitions during initial swash events (Trial 1) on the 30% cobble and 50% cobble beach compositions. Only the least dense and largest munitions reached incipient motion during the bore uprush impact. In addition to the swash hydrodynamics, the size and density of the munitions relative to the beach bed roughness have been shown to play a significant role in whether a munition would mobilize downslope or bury. As the density of the munitions increased, total downslope munition migration decreased. Interestingly, the response of the beach profile and overall munition mobility on the 50% cobble beach was nearly the same behavior observed for the 30% cobble beach with net-offshore directed sediment transport and offshore munition migration. However, the mixed grain beach morphology and munition behavior were much different than the pure sand and cobble beach behaviors. For the pure sand, 30% cobble and 50% cobble beach compositions, the least dense munitions (M40R2) were observed to move and follow the direction of the runup, but during all events resulted in net-offshore directed migration. Munition migration distances for all munition types on the pure sand and mixed grain beach compositions generally increased as the percentage of sand

in the mixture increased, implying the roughness of the beach is potentially a controlling factor for beach development and object mobility.

Swash bore velocities developed on the 100% cobble beach were not significant enough to induce munition mobility during uprush or backwash for any of the munition types nor at either of the initial deployment locations. Instead, all munitions on the cobble beach were observed to be covered by rolling cobbles. Specifically, the M20 munitions at both locations were completely covered after five consecutive swash events due to morphological burial of net-onshore directed sediment transport of the cobble beach during uprush. The beach profiles and munition mobility on the pure cobble beach were subject to greater infiltration of water even though they initially were forced with the same initial swash conditions as the pure sand and mixed grain beach compositions.

Laboratory results guided NHWAVE numerical experiments to determine the influence of beach state (intermediate, steep) on swash bore acceleration and corresponding impact to munition mobility. We saw that the bore shape and forcing was highly influenced by beach slope, which could in and of itself influence munition mobility. A combination of model results and munition mobility number can be used to guide scenarios where munitions are expected to move.

The object mobility number, akin to the Shields parameter, is used to predict munition motion and is presently a function of water velocity and munition density. Extracted local intrabore near-bed backwash velocities and water depth at the instant of migration (roll) are used to calculate critical object mobility numbers. Object mobility numbers increased as munition density decreased and were the largest on the 50% cobble beach. Maximum slope correct object mobility numbers for each munition type and beach composition were calculated. Comparison between maximum bore velocities and bore velocities at the time of munition motion imply that water velocities did not have to reach the maximum observed for munitions to migrate on the sandy beach mixtures. With our laboratory and numerical model observations, we suggest that the accuracy in the object mobility number would benefit by including a friction term that accounts bed roughness, a bed slope modification for both uprush and downrush, and a bed infiltration/liquefaction modification to account for sediments that are more or less porous.

7 Future work

Improvements to object mobility number Based on the limited lab-based cases analyzed, the slope-corrected object mobility number showed potential for predicting munition mobility. However, the scatter in the predictions is too high to be used with confidence for field scenarios. We believe the addition of a frictional term in the object mobility number needs to be investigated to account for the bed roughness that we saw restrict the munition from migrating. In addition to a friction term, the munition mobility number should be modified for bed slope, infiltration/liquefaction. This would require a more extensive data set to assess the uncertainty in the estimates. Based on the runup hydrodynamics and pressure sensor measurements, we believe that the cobble beach was most influenced by infiltration, and from other larger scale experiments the PIs have completed in sandy sediments, we know that liquefaction of sediments can lead to burial of the munitions. Numerical experiments showed that uprush and downrush bore energy were heavily influenced by slope.

Sediment composition Beach composition had a significant effect on munition mobility. The beaches in this experiment consisted of a mixture of two grain sizes and at select mix rates. At 100% cobble, the munitions showed no mobility, while at 50%-50% cobble-sand mixture, munitions migrated significantly. The transition and threshold for movement remains unknown. Additionally, varying gradations of sediment size for both sand and cobble would likely influence mobility thresholds, and is more realistic of real beach compositions.

Effects of beach heterogeneity Limited field pictures suggest munitions can agglomerate in different parts of the beach alongshore and cross-shore. We hypothesize that alongshore variability in forcing and beach geometry (i.e., beach cusps) and heterogeneity of beach composition (patchiness) can lead to areas of concentration of munitions. Periodic aerial overflights of a known coastal FUDS region that has mixed grain sediments can help quantify munition displacements. In addition, aerial overflights of FUDS sites with mixed grains can inform munition placement in field experiments.

Assessing the effects of munition burial Munition burial was not explicitly investigated in this experiment. However, the amount by which

initially proud munitions buried throughout the experiments seems related to the sediment composition. To determine if munition exposure is a threat on mixed grain beach composition, variable initial burial status of munitions on several beach states should also be investigated.

Future Experiments The small double dam-break flume was ideal for a SEED project. However, a much larger, more energetic flume should be used for any proposed future experiments. Larger munitions should be included. The knobby covered munitions should be excluded. A more detailed description of the sediment (grain size distribution, porosity and permeability) should be provided. Experimental design will be based on hydrodynamic modeling information given through the NHWAVE simulations.

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A Appendix: List of Acronyms

ADPV: Acoustic Doppler Profiling Velocimeter
CACR: Center for Applied Coastal Research (University of Delaware)
DOD: Department of Defense
EMCM: Electromagnetic current meters
FOV: Field of view
FUDS: Formerly Used Defense Sites
NHWAVE: Non-hydrostatic wave model
PSA: Pressure sensor array
RPM: Rotations per minute
SERDP: Strategic Environmental Research and Development Program
UnMES: Underwater Munitions Expert System
UDM: Ultrasonic distance meter
UXO: unexploded ordnances
sUXO: surrogate UXO

B Appendix: CACR Flume Sensor Schedule

Table 4: Schedule for Cart Station Sensors (H#) and Buried (B#) Sensors

Sensor Type	X (Flume Coordinates,m)
H1	-5.13
H2	-4.25
H3	-2.36
H4	-2.02
H5	-1.57
H6	-0.65
H7	-0.13
H8	0.47
H9	0.87
H10	1.49
H11	2.38
H12	3.45
B1	1.49
B2	2.6
B3	3.4
B4	3.9

C Appendix: Velodyne LiDAR Post-Processing for Hydrodynamic Analysis

Reference Frame Transformations Point clouds generated in the field are first transformed onto a local coordinate system using known reference markers and GPS measurements of the site. In this case, all sensors employed for this experiment were mounted at different locations within the flume. Therefore, a common flume coordinate system with the origin (0,0,0) centered about the beach toe was defined. The vertical component ($z = 0$) is set to the bottom of the flume and the horizontal and lateral limits are bound between $x = \pm 5\text{m}$ and $y = \pm 0.3\text{ m}$, respectively. Maximum flume elevations stop at $z = 0.78\text{ m}$ (total flume height). Velodyne measurements are internally converted from polar measurements to cartesian coordinates local to the sensor's optical center. Therefore, the instrument orientation, relative horizontal distance from the toe, lateral location, and elevation from the bottom of the flume were measured and used for transforming the sensor measurements to the newly defined flume coordinate system. The orientation of the LiDAR mounting had to be resolved as well to account for a horizontal mounting position rather than the designed vertical orientation that the Velodyne measurements are internally collected as. Post processing also included removing measurements beyond the immediate flume region.

Point Cloud Density, Resolution, and Horizontal Coverage Point cloud density, and resolution were analysed in terms of coverage between $x = -0.25\text{ m}$ and $x = 5.1\text{ m}$. At the mounting location ($x = 5.1$), the Veodyne did not recover any measurements. Instead, the coverage began at $x = 4.7\text{ m}$ with an average of 1150 points per frame, (while scanning at 20 fps). Of those, the majority of the measurements were gathered near upslope, with 78 % of the total points per stationary frame resolved between $x = 3.5\text{ m}$ and $x = 4.7\text{ m}$. Thus, as distance from the instrument grew, measurements became more sparse. Lowest point numbers per frame were associated to the toe region between $x = -0.25\text{ m}$ and $x = 0.5\text{ m}$ (0.37 % of the total number of points per frame). Almeida et al. (2015) observed similar trends in decreased coverage during their field experiment and attributed it to a low angle of incidence. Beach composition also seemed to effect point cloud density. Notably, the 100 % cobble bed type showed a decrease in point generation to 850 points per frame generated using the same 20Hz frame rate. However, the first resolvable points closest to the Velodyne was not

affected, and remained at $x = 4.7$ m for all beach compositions.

Bathymetric Interpolation & Profile Selection The Velodyne will maintain a rotation speed within 3 RPMs of the configuration settings. However, the small variation in speed produces a small change in the azimuthal gap with each revolution. Thus, measurements appear as unorganized point clouds, collected along the 32 individual laser rays but are variable frame to frame. Fortunately, a higher resolution point cloud can be achieved than from any single stationary frame by concatenating the full duration of the stationary scans of similar trial type (pre- and post-). Note, the Velodyne optical center was 0.273 from the leftmost flume wall (-y) and was oriented horizontally to capture the bore. As a result, the individual laser rays spanned the length of the flume (x), but left gaps between each ray along the width of the flume that could not be filled by concatenating the frames. Furthermore, the design of the Velodyne made it such that the rays that fell within the flume bounds did not line up directly with the center of the flume (flume origin = 0.3 m from the wall). Therefore, several bathymetric interpolation schemes were applied to the concatenated point clouds to fill the horizontal and lateral measurement gaps. These interpolation methods were also compared. In all cases, the interpolation schemes were executed on a grid that encompassed the flume limits between $x = -0.25$ m and $x = 4.7$ m with spacing of 1 cm and $y = \pm 0.2$ m.

The matlab `griddata` interpolation function was originally applied to the concatenated scans. The method essentially interpolates a surface at specified query points and returns the values as a single row vector that can be reassigned into a mesh. There are five interpolation methods that can be applied (linear, nearest, natural, cubic, and v4). When applied to a pre-scan, the linear and natural `griddata` bathymetry appeared the most realistic to the raw concatenated values. Additionally, a profile view of the two bathymetric results showed to lined up properly with the bottom of the flume indicating there were no apparent misrepresentations of the unresolved features or over-smoothing effects. The cubic method results are also comparable to the linear and natural methods but a side view of the profiles reveals errors in the interpolated measurements that dip below the bottom of the flume. Similarly, nearest and the v4-spline methods cause undesired humps that misrepresent the true data. However, these are the only two methods that can extrapolate across the entire mesh area beyond the limits of where the true values end. The linear method for `griddata` was selected in part because results deemed favorable to the others and to effectively compare a simplistic method to the

more robust linear inverse distance weighting schemes.

A linear inverse distance weighting interpolation scheme, and a scale-controlled interpolation as described by Plant et al. (2002), were applied to the concatenated datasets as well. Although the methods are similar, the linear inverse distance weighting interpolation scheme is a deterministic method that uses a defined number of known points (based on a given distance from the unknown point) to produce a value at the unknown location. Values are calculated with a weighted average of the known points. The weight of each known value decreases the further away it is from the unknown location. The scale-controlled interpolation is a similar weighting interpolation method but reduces potentially contaminated datasets by controlling resolved length scales in the interpolated product through a smoothing weight function. In this case, the quadratic loess linear smoother is applied to yield a smooth estimate of the true bathymetry. In some cases however, the interpolator will falsely oversmooth or even amplify observations (aka, overshoots the estimates). Fig. 29 compares the three interpolation schemes, where in subplot c, the scale-controlled interpolation scheme misrepresents the unresolved portion of the scan. The result is rather noisy, with significant spikes in the regions between laser ray, but at sections of higher point cloud density look well interpolated and smoothed. Widening the region for the weighted interpolator to pull true measurements from helps reduce these issues but can result in overly smoothed bathymetry.

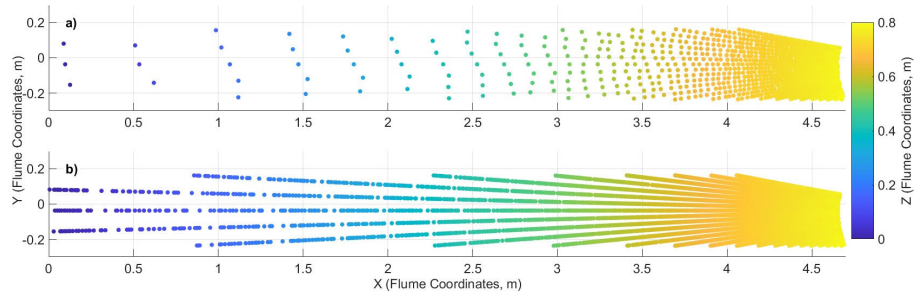


Figure 28: Pre-stationary scan of the pure sand beach leveled to the initial 1:7 slope. Single frame (a) compared to 20 seconds of concatenated frames (b).

While there are apparent interpolation artifacts as a result of the different schemes, the comparisons proved there was little lateral variability (y) in

morphological development between trials. Therefore, rather than arbitrarily selecting a horizontal transect to compare trial profiles by, an alternative approach was used. Instead, the flume is assumed to be laterally uniform and measurement gaps were instead filled by averaging the elevation measurements (z) along the width of the flume at every horizontal location (x). Final pre- and post- trial beach profiles were attained by linearly interpolating the scan over a defined quarry vector of $x = -0.25$ m and $x = 5.0$ m with 0.01 m spacing. This greatly reduced the processing time required compared to using the bathymetric interpolation schemes.

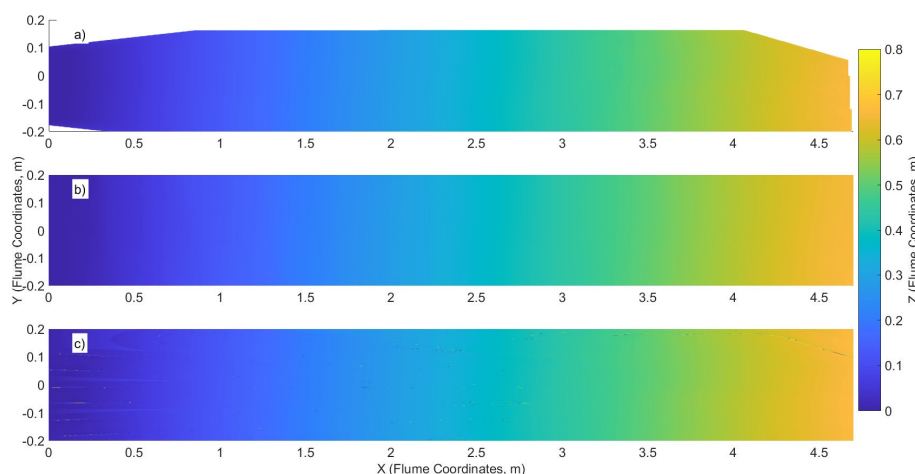


Figure 29: Bathymetric Interpolation scheme comparison for the sand beach composition showing a) Matlab linear griddata, b) Linear inverse distance weighting, c) Scale-controlled interpolation.

Separating water and bed measurements

Water detection with LiDAR can be extremely challenging due to specular reflective characteristics that reflect rather than uniformly disperse energy. Thus, returns generated over a smooth water surface are only achieved if viewed back by the sensor from the approximate perpendicular laser angle to the surface (Blenkinsopp et al., 2012). In this case, the 5 cm ambient water level could have been generating specular reflections prior to bore release and causing the low return rates at these offshore locations. It is also noted that the propagating bore was turbulent; textured predominately with bubbles and foam which could explain the improvement to the number of signal

returns obtained during bore release.

Previous laboratory studies utilizing LiDAR for capturing wave profiles have also increased signal returns through the addition of kaolinite, a clay mineral with a D_{50} of 20 μm , mixed into the fluid (Blenkinsopp et al., 2012). In the mixed grain and pure cobble trials, the pigment of the black cobble within the bed was shown to tint the clear water and increase turbidity levels. The textured surface, along with a change to the approaching incident angle caused by the bore, presumably increased surface detection by the LiDARs during bore release, runup, and rundown. Despite the sensors showing a capability of capturing the bore as it traverses upslope, it is difficult to discern the water from the bed as there is no delineation between the measurements. Furthermore, the non-stationary datasets show the time varying progression of the bore and therefore could not simply be concatenated to enhance horizontal resolution. Instead, each frame had to be analyzed individually.

To correct for the spatial variability between sequential frames, the transformed datasets were again assumed to be laterally uniform. Thus, measurement gaps were initially filled by averaging the elevation measurements (z) along the width of the flume at every horizontal location (x). To increase the resolution horizontally along the beach, each frame was linearly interpolated over a defined quarry vector of $x = -0.25 \text{ m}$ and $x = 5.0 \text{ m}$ with 0.01 m spacing.

Due to the laboratory setting, the pre-profiles of each trial were used as a baseline for separating the non-stationary frames into individual bed and water measurements. A minimum water depth was also added to the pre-profile measurements to account for sensor measurement noise. As such, a separation threshold (ST) was defined as the pre-profile plus the minimum depth. Thus, any sequential frame with elevations above this ST were identified as water and anything less than or equal to as the bed. Various minimum water depths were obtained and compared from calculating the Velodyne's unique noise floor (Appendix D). It should be noted that for very small water depths, the amount of incorrectly separated water measurements increased. Therefore, two favorable water depths were used (1mm and 15 mm) for measurement separation as well as create a window for which the extracted measurements are most reliable.

D Appendix: Lidar “Noise Floor”, Range, and Minimum Water Level Criteria

A critical component in accurately extracting the water dataset from the profile is to identify instrument precision “noise floor” and range. Precision being the repeatability of a measurement at a single location. To ensure proper bed and water extraction, the noise floor was defined as containing 99.7% of the measurements, or 3 standard deviations from the mean. Peak-to-peak excursion of the detrended measurements (maximum and minimum values) provided the total range in the sensor measurements.

Defining these two parameters for the Velodyne and Blickfeld relied on inspecting six individual scans. These scans included three stationary pre-datasets and the corresponding non-stationary datasets. The stationary scans were concatenated for their full duration while the first 3 seconds of the non-stationary scans were concatenated. It was important that the noise and range calculations were processed over the portion of the slope with the greatest sensor coverage area. Therefore, the scans were reduced to a cross-shore region in which the total number of generated points, per 0.5 m cross-shore section, was greater than 5%. For the Velodyne datasets, this was between $x = 3.5$ m and 4.5 m on the 50 % cobble bed and $x = 3$ m and $x = 4.5$ m on the 100 % cobble bed; the Blickfeld region was larger and spanned across $x = 2.5$ m to $x = 4.5$ m on both the 50 % and 100 % cobble beds. Next, the reduced scans were detrended and relative range and precision values for the selected group of scans were calculated from detrended measurement maxima, minima, mean, and 3 standard deviations values.

To deduce one precision and range value from the four scans, the statistical values were averaged (Table 5). Maximum noise floor and range values observed varied significantly by bed for the Velodyne, with the maximum noise calculated across the 100 % cobble as 15 mm. Conversely, the variations in noise were less for the Blickfeld datasets, but had a maximum noise value of 59 mm from the 100 % cobble bed datasets.

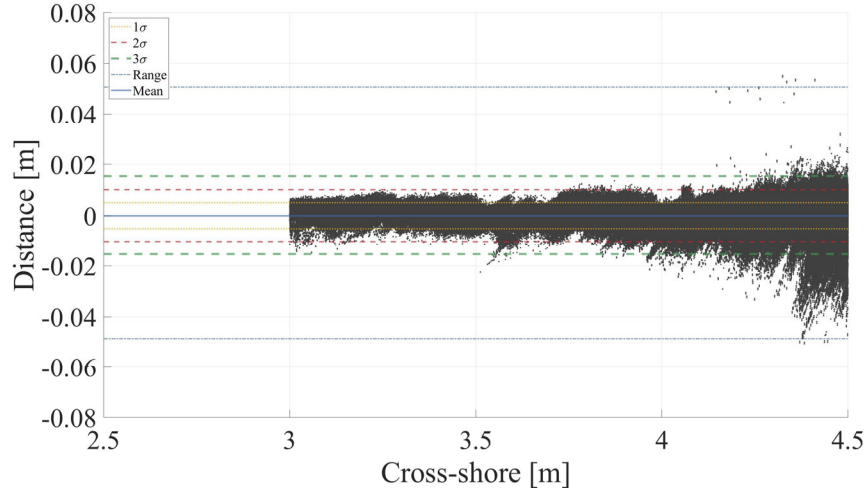


Figure 30: .
Velodyne noise floor exploration Several stationary scans were concatenated and the scattering in measurements is revealed.

While the noise floor values were not used as the final minimum water level (min) s, they were used initially to inspect how separation and hence maximum runup height and inundation values might be affected. Since true maximum inundation measurements existed for the 50 % cobble trials, the water separation process was applied to these dataset from the two LiDARs but with varying minimum water levels applied. The final minimum water level was determined when the percent error between observed inundation values were small ($\leq 1\%$). The same minimum water levels were applied to the Velodyne and the Blickfeld datasets and started with the maximum noise floor values of the two bed types for each of the sensors. Additional s applied were the largest first and second standard deviation from the mean values of the two bed types and sensors. A summary of the tested s is presented in Table 4, along with the associated maximum inundation percent errors. It is important to recall that the Blickfeld coverage does not exceed 4.3 m in the cross-shore direction. Since the observed maximum inundation for the 50% cobble bed type was beyond the observable coverage area, the percent errors for the Blickfeld will already be notably greater than the Velodyne errors, even for small water values.

E Appendix: Reflectivity Investigation for capturing runup

For every distance measurement produced by the Velodyne is an associated calibrated reflectivity value between 0 and 255. A value of 0-100 indicates the return of a diffuse reflection (textured surface that scatter reflected energy) and a value greater than 101 indicate the return from a retroreflector (reflect light back to source with minimum scatter) where 255 represents an ideal reflection (MANUAL). It is important to note that zero is a valid reflectivity value. A null measurement will occur when the response of both a measurement and reflectivity are zero and are not recorded by the Velodyne. Analysis of the Velodyne non-stationary datasets did not recover any retroreflectors (within the bounds of the flume) and was only composed of diffused reflections (0-100). Prior to separating the water from the bed, a visual inspection of the datasets at lower cross-shore positions, during the bore release, and where the water was more obvious than in the upper sections, reveal reflectivity values of 0-20 correlated well with the traversing bore and hence the water. Unfortunately, the observable bed also included reflectivity values between 0-20, and went as large as 100 in the upper sections of the slope. Thus, it was concluded that the water could not be distinguished from the bed based solely on reflectivity values for the Velodyne datasets.

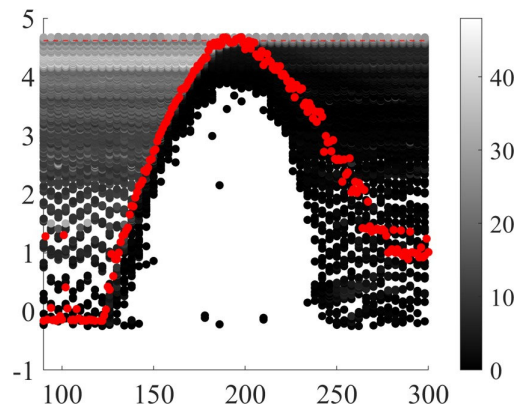


Figure 31: Example of the runup extent extracted using intensity values of the Velodyne LiDAR from a single stationary scan. Red line shows the runup extents extracted using the water separation methods.

F Appendix: Unique Series Munition Measurements

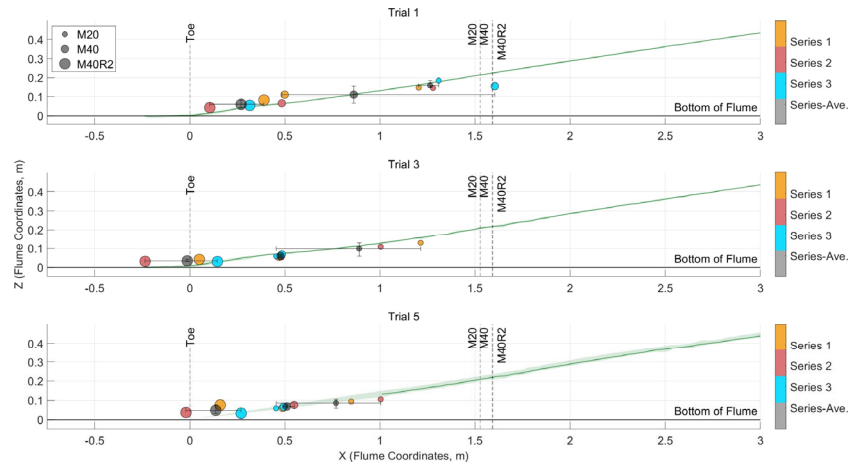


Figure 32: Munition migration measurements for Sand: X = 1.5 m

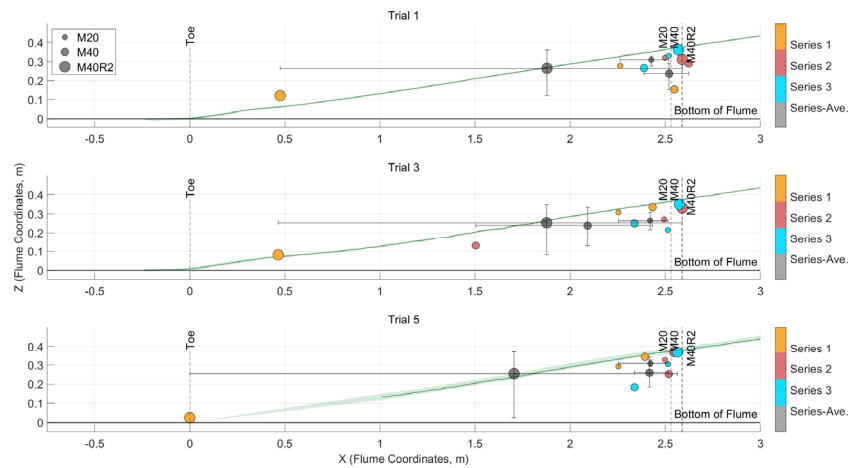


Figure 33: Munition migration measurements for Sand: X = 2.5 m

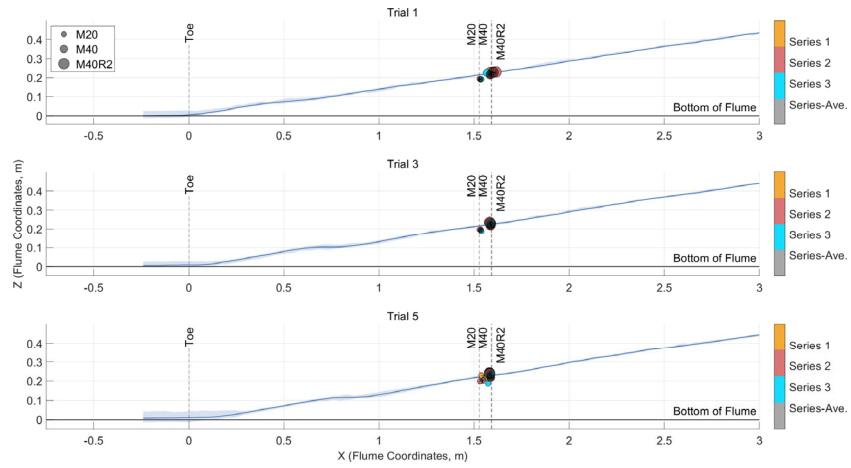


Figure 34: Munition migration measurements for Cobble: $X = 1.5$ m

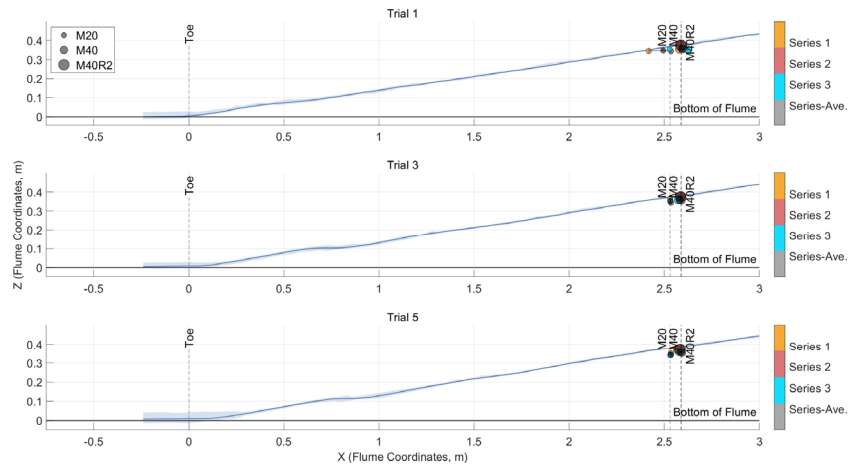


Figure 35: Munition migration measurements for Cobble: $X = 2.5$ m

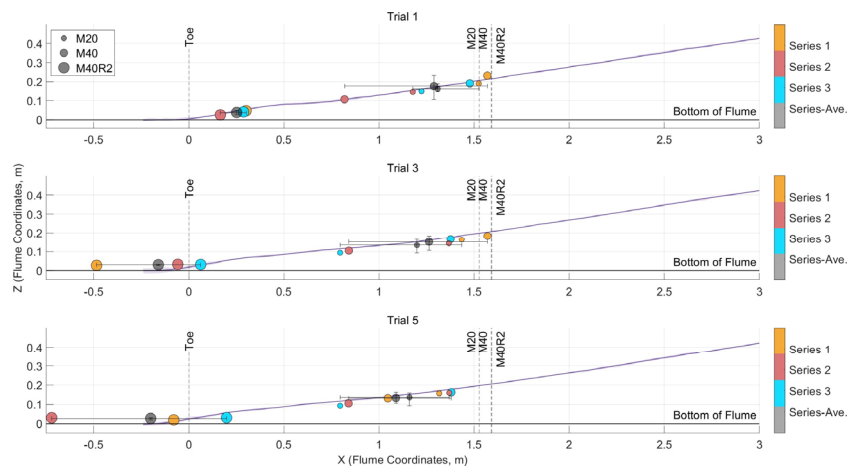


Figure 36: Munition migration measurements for 30% Cobble: X = 1.5 m

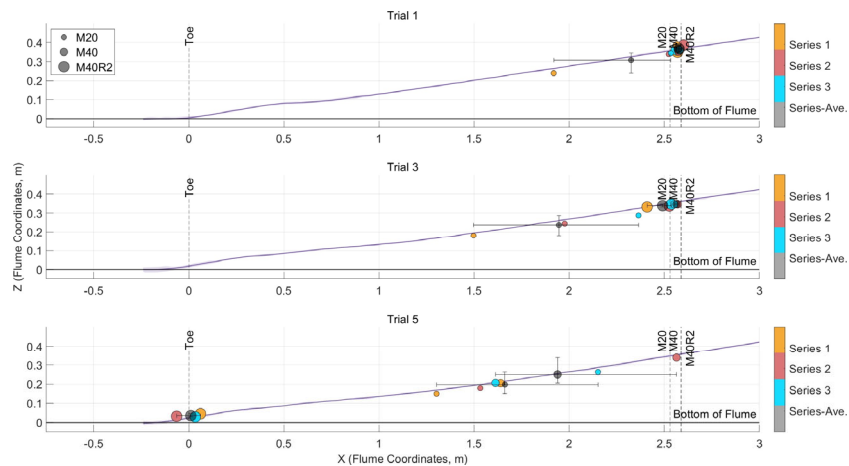


Figure 37: Munition migration measurements for 30% Cobble: X = 2.5 m

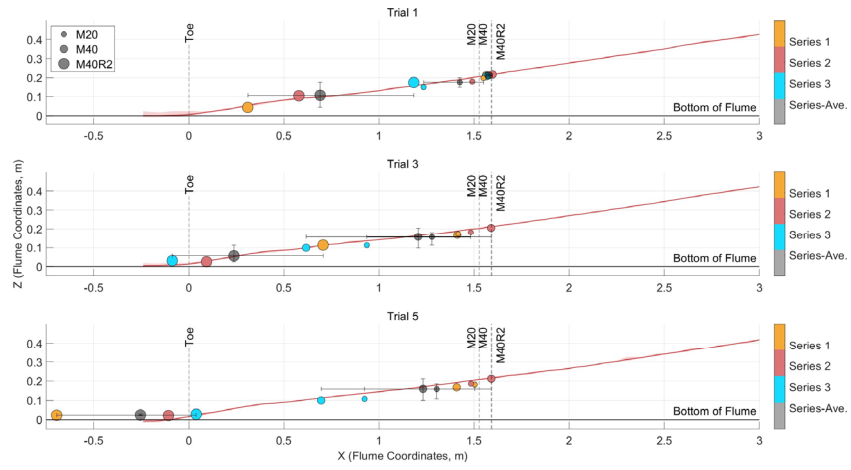


Figure 38: Munition migration measurements for 50% Cobble: X = 1.5 m

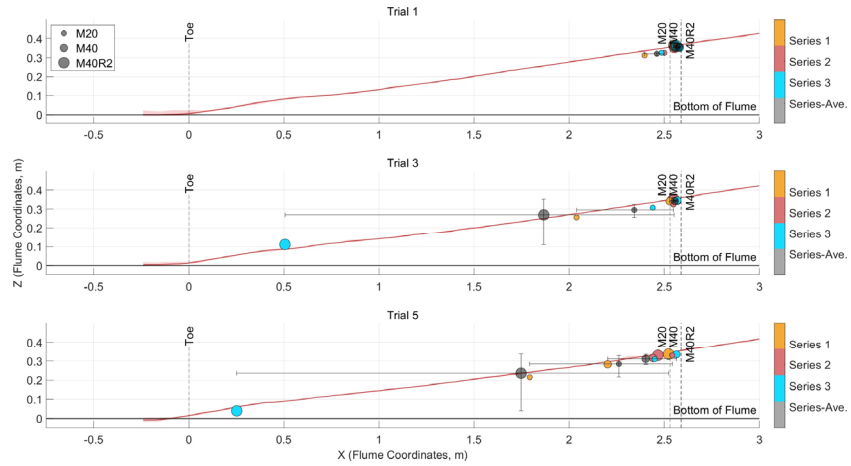


Figure 39: Munition migration measurements for 50% Cobble: X = 2.5 m