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Modeling Munitions Mobility and Burial in a Micro-tidal Estuary

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14. ABSTRACT
The study of underwater unexploded ordnances (UXOs) mobility and burial in underwater environment is of paramount importance due to the large number of sites potentially contaminated with munitions. This project, called MINELAB, aimed at modeling the fate of munitions displaced over or buried into the heterogenous sedimentary bed of a micro-tidal estuarine site, subjected to both fluvial and marine forcing. The objective was twofold: (1) to directly observe the combined effect of river flow, water waves and tide on the mobility and burial of UXOs; (2) to predict the behavior of UXOs subjected to the combined action of river discharge and waves in a micro-tidal environment characterized by mixed sediments.
Results of field tests showed that UXOs deployed in areas characterized by different soil material behave differently. Once placed on the muddy riverbed, the UXOs almost instantaneously got buried and did not move. Just the smallest and least dense UXO showed some migration and resurfaced at times. On the other hand, the UXOs remained proud on the sandy seabed, until a wave storm produced a significant morphological seabed evolution, likely fostered by fluidization of the sandy bed, that caused their complete burial. The largest observed migration distances were of the order of 7 m. The Underwater Munitions Expert System (UnMES) simulation, aiming at reproducing the UXOs behavior during the field test performed at sea, showed a migration distance in the range 0m to 5m, in agreement with the observations. Predicted burial depths were, instead, smaller (50% to 75% of the UXO diameter) than those observed in the field (over 100% of the UXO diameter).

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List of Acronyms

ADCP	Acoustic doppler current profiler
AHRS	Attitude and Heading Reference System
ASV	Autonomous Surface Vessel
CMRE	Centre for Maritime Research and Experimentation
CNR-IRBIM	National Research Council – Institute of Marine Biological Resources and Biotechnologies
DARS	Diver/Asset Recovery System
DICEA	Department of Civil Engineering and Architecture
DII	Department of Information Engineering
DMM	Degrees Decimal Minutes
DoD	Department of Defense
DPR	Directional Pinger Receiver
GPM	GeoPoseModule
GPS	Global Positioning System
DGPS	Differential GPS
HDOP	Horizontal Dilution Of Precision
IMU	Inertial Measurement Unit
ISPRA	Italian Institute for Environmental Protection and Research
ITS	Intelligent Tracking System
MEC	Munitions and Explosives of Concern
MR	Misa River
MR[1]	Munition Response
NRL	Naval Research Laboratory
PDOP	Positional Dilution Of Precision
RTK	Real-Time Kinematic
S.D.A.I.	Sminamento Difesa Anti Mezzi Insidiosi
SEED	SERDP Exploratory Development
SERDP	Strategic Environmental Research and Development Program
SGS	Sena Gallica Speculator
SN	Satellite Number
SON	Statement of Need
UBL	Underwater Locator Beacon
UNIVPM	Università Politecnica delle Marche
UnMES	Underwater Munitions Expert System
UTM33N	Universal Transverse Mercator - Zone 33 - North
UXO	Underwater Unexploded Ordnance
VDOP	Vertical Dilution Of Precision
WGS84	World Geodetic System 1984

[1] Used for references.

List of Symbols

a	Amplitude of the near-bed orbital velocity
B	Burial
D	Object diameter
D_{50}	Median sediment diameter
f_w	Wave friction factor
g	Gravitational acceleration
h	Water depth
Hs	Significant wave height
k	Bed roughness
KC	Keulegan-Carpenter number
M	Migration
pb	Percentage of burial
q0, q1, q2, q3	Quaternion components
R	River discharge
S_0	Object relative density
Tp	Wave peak period
U	Near-bed velocity
U_b	Bottom current velocity
$U_{b\|\|}$	Bottom current velocity parallel to waves
U_c	Depth averaged current velocity
U_w	Near-bed orbital wave velocity
W	Waves
z_b	Burial depth
α	Angle between waves and UXO major axis
θ	Sediment Shield parameter
θ_{cr}	Critical object mobility parameter
θ_{obj}	Object mobility parameter
ρ_{obj}	Object density
ρ_w	Water density
ρ_{sed}	Sediment density
$\rho_{sed,cr}$	Critical sediment density
β	Angle between U_w and U_b
κ	Von Karman constant

Keywords

UXO, mobility, burial, estuarine environment, field experiments

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Abstract

Introduction and Objectives

The study of underwater unexploded ordnances (UXOs) mobility and burial in underwater environment is of paramount importance due to the large number of sites potentially contaminated with munitions. This project, called MINELAB, aimed at modeling the fate of munitions displaced over or buried into the heterogenous sedimentary bed of a micro-tidal estuarine site, subjected to both fluvial and marine forcing. The objective was twofold (Figure s- 1): (1) to directly observe the combined effect of river flow, water waves and tide on the mobility and burial of UXOs; (2) to predict the behavior of UXOs subjected to the combined action of river discharge and waves in a micro-tidal environment characterized by mixed sediments.

Technical Approach

Some preliminary Delft3D numerical modeling was conducted to better characterize the hydro-morphodynamics of the test site, reducing uncertainties and risk associated with the design of the field experiments. These were performed at different locations in the estuarine area, to assess the role of different actions (e.g., river flow, waves of various nature) and soil material on the UXO mobility and burial. Results of such field experience, together with the data collected by an integrated monitoring system operating in the study area, were used to contribute to the validation of a single tool that combines the modeling of both hydro-morphodynamics and object mobility, with the aim to reproduce the deployed UXO motion.

Results

Results of field tests showed that UXOs deployed in areas characterized by different soil material behave differently. Once placed on the muddy riverbed, the UXOs almost instantaneously got buried and did not move. Just the smallest and least dense UXO showed some migration and resurfaced at times. On the other hand, the UXOs remained proud on the sandy seabed, until a wave storm produced a significant morphological seabed evolution, likely fostered by fluidization of the sandy bed, that caused their complete burial. The largest observed migration distances were of the order of 7 m. The Underwater Munitions Expert System (UnMES) simulation, aiming at reproducing the UXOs behavior during the field test performed at sea, showed a migration distance in the range 0m to 5m, in agreement with the observations. Predicted burial depths were, instead, smaller (50% to 75% of the UXO diameter) than those observed in the field (over 100% of the UXO diameter).

Benefits

Results of the project provided information on UXOs mobility and burial in an estuarine environment, characterized by multiple forcing actions and mixed sediments. On the one hand, such characteristics make the site different from other sites usually studied in the literature, thus interesting; on the other hand, they make the analysis very complex. Field observations provided a baseline data set for verification and calibration of our model set up to predict munitions mobility and burial, based on the combination of Delft3D and UnMES models. Due to (1) the limited duration of both the experimental campaign and project and (2) the measurement procedures and techniques tested for the first time within this project (some fairly innovative in the overall), just few data were produced to feed UnMES. A longer field test using more instrumentation to characterize the study area and more precise and consolidated measurement procedures would provide valuable results for the validation of UnMES.

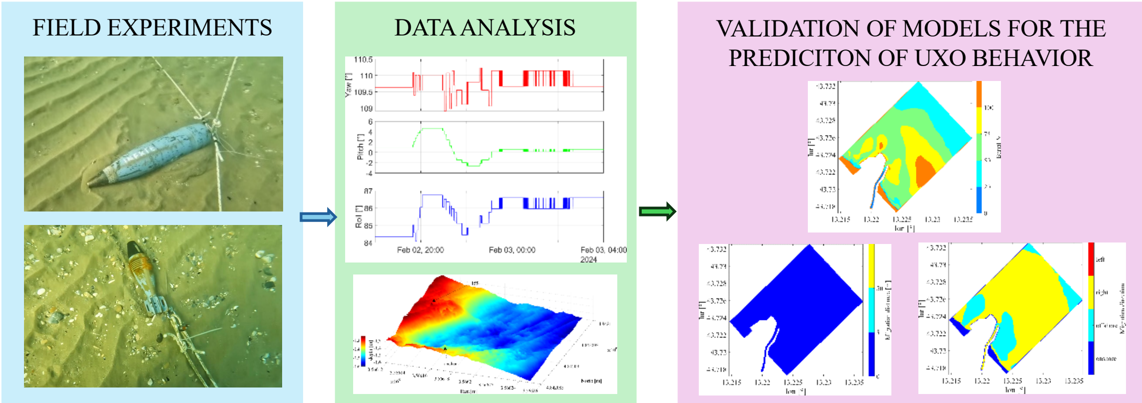

Figure s- 1. MINELAB workflow.

Executive Summary

Introduction

Many studies have been performed in the latest decades to investigate the mobility and burial of munitions in underwater environments, a topic of paramount importance, since there are many underwater sites potentially contaminated with munitions. UXO behavior has been initially studied through field and laboratory experiments, recently complemented by numerical modeling aimed at predicting mobility and burial of objects.

Within the MINELAB project, we investigated the behavior of UXOs in a field site that presents characteristics different from those considered in the past research on munition mobility and burial. The proposed site is the Misa River (MR) estuarine area (Senigallia, Central Italy; Figure s- 2), which represents an optimal site for the analysis of the UXO fate due to the presence of both river and sea forcings, where different sediment types exist (from gravel and sand to silt and clay; as discussed in Brocchini et al., 2017). Furthermore, the site hosts an integrated monitoring system, deployed along the MR estuary and offshore since 2015 within the NICOP EsCoSed and MORSE projects, two collaborative efforts between the Università Politecnica delle Marche (UNIVPM, Ancona, Italy) and the US Naval Research Laboratory (NRL, Stennis Space Center, MS). Hence, the MR estuary is currently a highly monitored area, where the existing instrumentation is being collecting data for more than six years and is providing a large amount of environmental real-time information (Figure s- 2).

The field site offers unique characteristics, never taken into account in previous studies on UXO mobility and burial. Being it an estuarine environment, it is influenced by several forcing actions, with river current, sea waves and tidal motion being the main ones. Further, the bed soil is characterized by heterogeneous material (Consorzio Di Bonifica Delle Marche, 2020), meaning that a combination of cohesive, weakly cohesive and non-cohesive areas exists within the MR estuary and nearby nearshore, this giving a complex scenario in terms of bed-morphology evolution and hydrodynamics. On the one side, the study area represents a complex environment, both from the hydrodynamic and morphological viewpoint, where observations on UXO mobility have never been taken. On the other side, such observations are exploited to validate a model for the fate of UXO in such a complex environment.

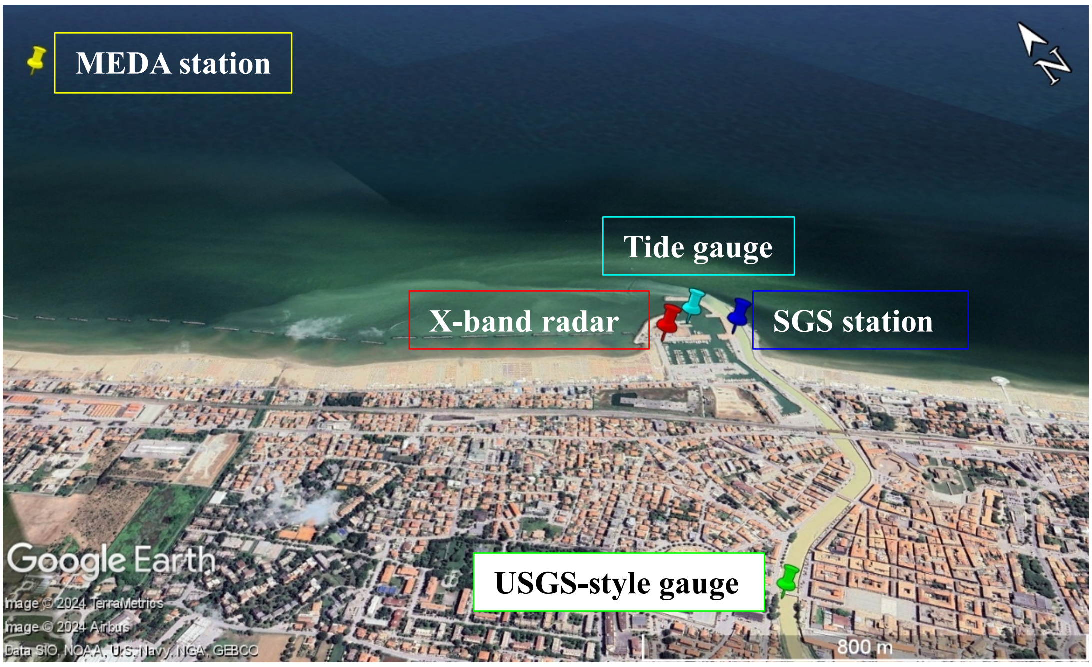

Figure s- 2. Instrumentation installed within and nearby the MR estuary.

Objectives

The objective of the MINELAB project was to model the combined role of river and marine forcings on the mobility and burial of underwater UXO in a micro-tidal estuarine environment characterized by mixed sediments. Our primary goal was to carry out field observations of the fate of munitions displaced over or buried into the heterogenous sedimentary bed of a micro-tidal estuarine site, subjected to both fluvial and marine forcing. Subsequently, such field observations, together with forcing measurements, were used to run and validate a numerical modeling suite, consisting of Delft3D hydro-morphodynamic simulations coupled with the Underwater Munitions Expert System (UnMES), a computer-based probabilistic expert system to predict mobility and burial of underwater munitions.

Technical Approach

The first phase of the project included some preliminary modeling of the MR estuarine area using the Delft3D suite, based on an already available setup (Baldoni et al., 2021, 2022) and on the collected data, to properly design the field experiment and choose the optimal locations for the UXO deployment. To such scope, simulations were also performed in collaboration with the research groups of NRL-Stennis Space Center (leader Allison Penko) and Corvus Works UG (leader Peter Menzel), using their mobilization and burial models. Results gave a first estimate of some important indicators, such as the probability of burial, mobilization, migration distance and migration direction. During the first phase, we also collected both real inert ammunitions and surrogates from a dedicated service of the Italian Army and a local blacksmith, respectively (Figure s- 3). Ordnances were filled with mixtures of sand, gravel, iron and expanded polyethylene to reach the desired weight of the objects.

Figure s- 3. Left: Inert ammunitions painted in “Steel Blue”. Right: Steel cylinders built by a local blacksmith.

In the second phase of the project, we designed the experimental plan and carried out all the permits and authorizations procedures in order to perform the field experiments. Our study was also promoted to some Italian Navy services (e.g. diving and demining services) that finally supported us in the design of the experiments and during some retrieval operations.

Field experiments were performed in November 2023-February 2024, i.e. the period that typically presents the most energetic wave events, for a total of five tests:

- three tests in river-dominant conditions (two 500 m upstream of the river mouth and one 200 m upstream of the river mouth), namely Test 1 and Test 4, and Test 2;
- one test just offshore of the river mouth, where the strongest sea-river interaction occurs, namely Test 5;
- one test 300 m offshore of the river mouth, where the sea prevails, namely Test 3.

Three (four) objects were dropped from the water surface by one of the two divers of Senigallia Servizi (contracted for this activity) at the river (sea) locations. The deployment operations were planned on the basis of three aspects. First, meteorological conditions had to be adequate to allow a safe deployment operation. Second, tests should have been performed in periods when events of significant sea forcing (sea storms), river discharges (intense rains) and mixed sea-river forced events were expected to occur. Third, the duration of the project had to be respected.

Each test consisted of three different phases: deployment, intermediate measurements and retrieval. The objects were tied, in series, to a reference anchor using slack ropes with the aim of: 1) not losing them and, at the same time, 2) leaving them free to move as much as possible. Moreover, an acoustic pinger was linked to each object. During the field deployment phase, a diver placed both the anchor and the UXOs on the riverbed/seabed and recorded their positions using a GeoPoseModule (GPM) designed and realized by ANcybernetics, a spin-off of the Marche Polytechnic University. GPM is for logging the position of objects at a determined time at the sea surface of the local vertical and it was, therefore, attached to a surface buoy carried by the diver (see Figure s- 4). The diver also measured the burial of the objects using a millimetric rod. During the second and third phases, the procedure was the same of the deployment day, with the diver searching for the objects and recording their position using the GPM. Finally, the objects were retrieved by divers of either the Italian Navy or Senigallia Servizi. To improve the accuracy of the position measurements of the objects, the GPM data were taken twice and MultiBeam surveys were performed by SOCOTEC Italia S.r.L, which also made its own position measurements, to be combined with the GPM data. Furthermore, a 155mm UXO was internally instrumented with one GPM to monitor its accelerations and rotations, this representing a fairly innovative approach of monitoring.

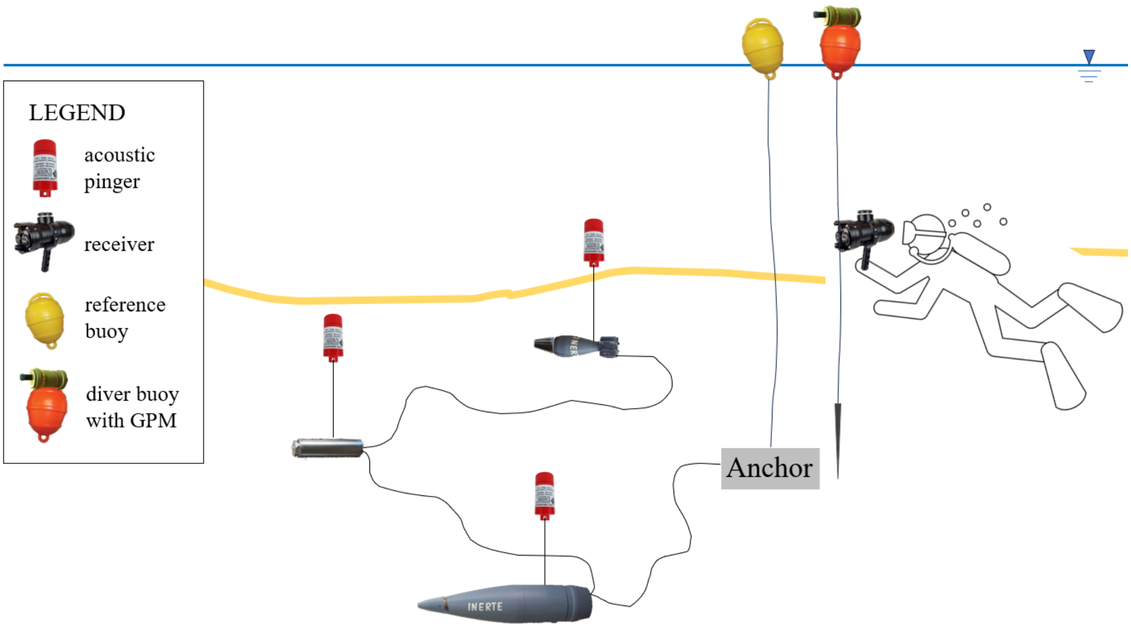

Figure s- 4. Sketch of the experimental setup.

Data analysis was performed during the third phase of the project, where data of UXO position and burial were interpreted in relation to hydrodynamic forcing actions. In such final phase, the validation of a model used to predict munition behavior in the estuarine site was also performed. First, a Delft3D simulation was run to obtain current and wave fields and seabed evolution for the longest test carried out from December 20th to January 17th. Then, Delft3D results were used as inputs, together with objects characteristics, for running UnMES.

Results and Discussion

Results of preliminary Delft3D numerical simulations showed that, in the overall, the riverbed evolution is mainly affected by the action of the river, with larger changes at the increase of the discharge. A moderate river discharge causes the erosion of the riverbed and sediment expulsion out of the river mouth. On the contrary, waves bring sediments inside the river mouth, thus promoting upriver sediment transport. The opposite actions of river and sea manifested clearly on the evolution of the MR inner mouth bar (Baldoni et al., 2021). This work reveals that the bar has a dynamical evolution mostly affected by the river discharge and the waves, while the tide only modulates the action of the two main forces. Moreover, the sediment expulsion out of the river mouth by the river discharge dominates over the upriver transport by the waves. In fact, river discharges comparable with the 1-year return period discharge induce downriver bar migrations much larger than the upriver displacements due to 10-years return period waves. This scenario of dynamical evolution of the river mouth bar, was taken into due account during the definition of the experimental plan, the latter to be dynamically adapted in time in relation to the bar evolution and possible maintenance/dredging works carried out by the local authorities.

Prediction of UXO mobility and burial were provided by NRL and Corvus Works UG. The simulated scenario was characterized by a discharge peak of 100 m^3/s and a wave storm from NNE with a maximum wave height of 2m. In the simulations, the bed composition was modeled as pure sand in the sea and a mixture of cohesive material, sand and gravel in the river. Numerical results showed that, under the simulated forcing scenarios, a 155 HE projectile:

- would very likely bury in the river with predicted burial depth of about 40% of the UXO diameter (reaching 77% at the river mouth) from Corvus Works' model and >100% from NRL's model;
- would very likely bury 50% to 100% in the nearshore area and 20% to 50% offshore;
- the most probable migration distance is expected to be in the range of 0 to 5 m, longshore directed either towards SSE when deployed North of the river mouth and offshore, or towards the onshore when deployed in front of the river mouth and South of it.

With reference to Table s- 1, results of field experiments showed that, during Test 1, 2 and 4, performed along the river, the heaviest UXOs got buried very quickly into the muddy riverbed because their buoyant weight exceeded the bearing capacity of the muddy sediments. Once head-down stuck in the riverbed, it is unlikely that they moved. Observed migration distances, in the order of few meters, might be due to adjustments of the UXOs over a sloped bathymetry as well as measurements inaccuracies. Some small impact burial was observed just once. On the other hand, the smallest and least dense objects, i.e. the 60mm mortar, showed a different behavior, remaining at the riverbed or resurfacing after being buried. The 60mm munition behavior seems to be affected by the local composition, characteristics, and sorting of the riverbed, and it is more complicated to predict without further analyses. Such object also showed the largest migration distances, probably moving as a single unit with the muddy bed, its motion being facilitated by the sloped bathymetry.

In Test 3, performed 300 m offshore of the river mouth, the UXOs remained at the sandy seabed until a moderate wave storm (maximum significant wave height of 2.3m in 12m water depth) caused the seabed fluidization with subsequent burial of the objects. Assuming a small percentage of burial before the onset of the storm, is it likely that the objects mobility threshold was exceeded due to the wave action. Therefore, UXOs experienced some migration, of the order of some meters before getting completely buried. The smaller displacements observed prior to the storm occurrence are likely due to the seabed modification, suggesting some sediment transport in the same direction of the UXOs' motion.

Test 5 was performed at the river mouth in a week characterized by very mild sea conditions, therefore UXOs remained at the seabed without experiencing any significant migration. Data recorded by the GPM embedded in the 155mm UXO confirmed the almost negligible mobility of the object, that only rolled slightly (2°).

Table s- 1. Synthetic results of burial (B) and migration (M) of the objects deployed during the five field experiments. Here, migration represents the displacement between the retrieval and the deployment times; burial is the final burial. Migration values were estimated combining different information, such as position measurements, MultiBeam surveys, image and video products.

	UXO type	**155**	**155 cylinder**	**155 instrumented**	**105**	**120**	**60**	**60 cylinder**
Test 1 (river)	**B [cm]**	50					resurfaced	23
	M [m]	-					3.2	1
Test 2 (river)	**B [cm]**		50		60		-	
	M [m]		1.3		1.7		5.0	
Test 3 (sea)	**B [cm]**	65			60	62	56	
	M [m]	4.5			5.2	4.9	7.3	
Test 4 (river)	**B [cm]**	85			90		resurfaced	
	M [m]	0.9			1.4		3.4	
Test 5 (mouth)	**B [cm]**	-		-	-		-	
	M [m]	-		-	-		-	

Globally, results of field tests did not differ much from the prediction of the preliminary simulations. The muddy riverbed caused the almost instantaneous burial of almost all UXOs, which did not move significantly, also because no important river discharge events occurred during the deployment period. The observed burial depth was much larger than that predicted by the simulations. For the test performed at sea (Test 3), the objects got completely buried due to a NNE wave storm. The UnMES simulation of such experiment predicted burial depths (50% to 75% of the UXO diameter) smaller than the observed ones (>100% of the UXO diameter), while the modeled most probable migration distance was within the range 0m to 5m, in agreement with observed displacements (maximum 7m).

Implications for Future Research and Benefits

At the end of the project, we would have expected to have new predictions and observations for the role of waves and river currents in a parameter space and sedimentary scenarios that presently have not been sampled for munitions mobility and burial. The effect of different sediment types was observed in our field tests, resulting in completely different UXO behavior in river and sea. The bed sedimentary composition turned out to be the parameter mostly influencing the burial of the objects and, therefore, a good knowledge of the sedimentological characteristics of the river/seabed material is essential to predict munitions response. However, due to the absence of significant precipitations, we could observe neither the effect of river discharges on UXOs deployed in the riverbed, nor the combined action of river and sea forces. Performing a new field campaign, lasting for a longer period, and using improved and consolidated measurement procedures, would allow the creation of a new dataset for validation of predictive models. In fact, the validation of such models over multiple forcing actions and sediment scenarios is essential to let them become useful tools for site managers and regulators.

Objective

This SEED project aimed at investigating the process of mobility and burial of UXO in a microtidal estuarine environment, characterized by the interplay between river and marine forcings over a heterogeneous soil made of a mixture of cohesive and non-cohesive materials. Our objectives were: (1) to observe directly the effect of different actions (river flow, water waves and tide) and their combination on ammunition mobility and burial; (2) to predict the processes of mobility and burial of UXOs subjected to the combined action of river discharge and waves in a micro-tidal environment characterized by mixed sediments (from gravel and sand to silt and clay). Field observations of UXO behavior were used as validation data set for the probabilistic model UnMES. Given the short duration of the project, which coincided with relatively mild weather conditions, it was possible only to observe the effect of a moderate wave storm on munitions mobility and burial. It would be useful to perform a longer field campaign to observe different forcing scenarios and complete the data set. In fact, although several field and laboratory observations (MR-2224, MR-2647, MR-2319, MR-2320, MR-2410) have been synthesized to provide preliminary testing for mobilization models (e.g., MR19-1126, MR21-1081), the task of demonstration for predictive models is still far from being satisfactory. Moreover, a notable deficiency of observations of munitions mobility and burial exists at sites characterized by cohesive sediments, even if many UXO contaminated sites lay partially or wholly in mixed-cohesive or cohesive sediment environments.

The experiments performed within the MINELAB project showed the great importance of the sediment type for the burial process, suggesting to properly characterize the river/seabed material with detailed sedimentological surveys. Moreover, field tests highlighted the primary role of the diver in the measurement procedures, meaning that timing and precision of measures are largely influenced by the diver's activities. Thus, future works will have to consider measures to reduce the influence of the diver's positioning. Other expedients to improve the accuracy and quality of measures were already implemented during the field activities: (1) to tie the tracking system to a surface buoy to let it record outside of the water; (2) to repeat the measurements twice or even three times; (3) to perform the measurement using different instruments; (4) to perform MultiBeam surveys.

The MINELAB project and possible future research respond to the SERDP Exploratory Development (SEED) Statement of Need (SON), which calls for particular interest on the topic of "address development of predictive models and understanding of the physical processes that are responsible for burial, migration, and re-emergence of UXO in underwater environments", particularly "during extreme hydrodynamic events". Moreover, our study site, i.e. the Misa River (MR) estuarine area, is characterized by shallow water depths and experiments were performed in depths less than 5 meters, which addresses the "specific need for systems that can operate in depths less than 5 meters".

Background

Many studies have been performed in the latest decades to investigate the mobility and burial of munitions in underwater environments. This is a topic of paramount importance, since UXO metal casings are subjected to corrosion and consequential leakage of degradation products into the surrounding environment (Edwards et al., 2016), a much more relevant issue when occurring in coastal waters. Furthermore, the U.S. Army Corps of Engineers and the Navy have identified more than 400 underwater sites potentially contaminated with munitions. Most of these areas are in shallow waters where ammunitions represent a threat to human health and the environment. Risk assessment is essential to identify remediation priorities for these sites. Therefore, a probabilistic expert system, UnMES (MR-2227), which combines field data and modeling to assess munition burial and migration and provide remediation guidance, is under

development. Laboratory and field experiments investigating the processes of motion and burial of UXOs (both real ammunitions and surrogates) under various forcing actions, in different bed materials, provide critical data sets to be integrated into UnMES.
Laboratory tests have been carried out using both munition surrogates and objects of canonical shapes, like spheres and cylinders, also analyzing their behavior over hard substrates of various roughness (MR-2410) and beds of different and heterogeneous material (MR21-1333). These works highlighted the importance of the soil type in both UXO migration and burial. The burial behavior is strongly affected by the type of soil. Specifically, the burial process can be split into two different steps: impact and burial. The UXO impact onto the bed is more relevant for coarser and muddy soils, whereas the subsequent burial is more important on non-cohesive, sandy soils (Wilkens & Richardson, 2007). In relation to the soil type, field observations of UXO burial were also carried out in coastal areas and combined to the modeling of the dynamic wave-seabed interaction to evaluate the instability criteria and sediment liquefaction, especially in sand-dominated areas (Klammler et al., 2020, 2021). A significant data gap was identified regarding MEC in shallow, cohesive-sediment environments, where munitions phenomenology is less clear (MR-2730).
State-of-the-art research has shown that the munitions caliber and relative bulk density have the most important effect on the UXO maximum burial depth (Klammler et al., 2020). Munitions with densities greater than the sediment are more likely to bury, while those less dense are more likely to mobilize in energetic conditions (MR-2320, MR-2319).
Different types of forcing have been applied in laboratory tests, allowing for the observation of munition behavior under unidirectional and oscillatory flows, with a focus on the initiation of motion of the objects at hand, e.g. through the analysis of the Shields parameter. Suitable formulations have also been found for the interpretation of the initiation of motion of munitions of different shapes subjected to unidirectional and oscillatory flows (e.g., Cataño-Lopera et al., 2011; Friedrichs et al., 2016).
To better understand the fate of munitions in coastal environments and to complement laboratory and field observations, dedicated numerical modeling has been recently carried out using models aimed at predicting mobility and burial of objects laying on sandy soils (Chu et al., 2021a, b; MR-2227), although no model has been tested for microtidal, estuarine scenarios characterized by multiple forcing actions and soil mixtures with different properties.

Study area

Within the above framework, we proposed to investigate the behavior of UXO in a field site that presents characteristics different from those considered in the past research on munition mobility and burial. The site is the MR estuarine area (Senigallia, Central Italy; Figure 1), characterized by the presence of both river and sea forcings, where different sediment types exist (gravel and sand to silt and clay; as described in Brocchini et al., 2017). Furthermore, the site hosts an integrated monitoring system, deployed along the MR estuary and offshore since 2015 within the EsCoSed and MORSE projects, two collaborative efforts between the Università Politecnica delle Marche (UNIVPM, Ancona, Italy) and the US Naval Research Laboratory (NRL, Stennis Space Center, MS). Hence, the MR estuary is currently a highly monitored area, where the existing instrumentation is being collecting data for more than six years and is providing a large amount of environmental real-time information. The monitoring infrastructure is characterized by two remote sensor systems, i.e. the SGS video-monitoring station, equipped with four cameras recording the final MR reach, the estuary and the nearshore area (blue pin in Figure 1), and an X-band radar, which is able to collect data for the reconstruction of wave field and bathymetry (up to 6 km from the shore; red pin in Figure 1).

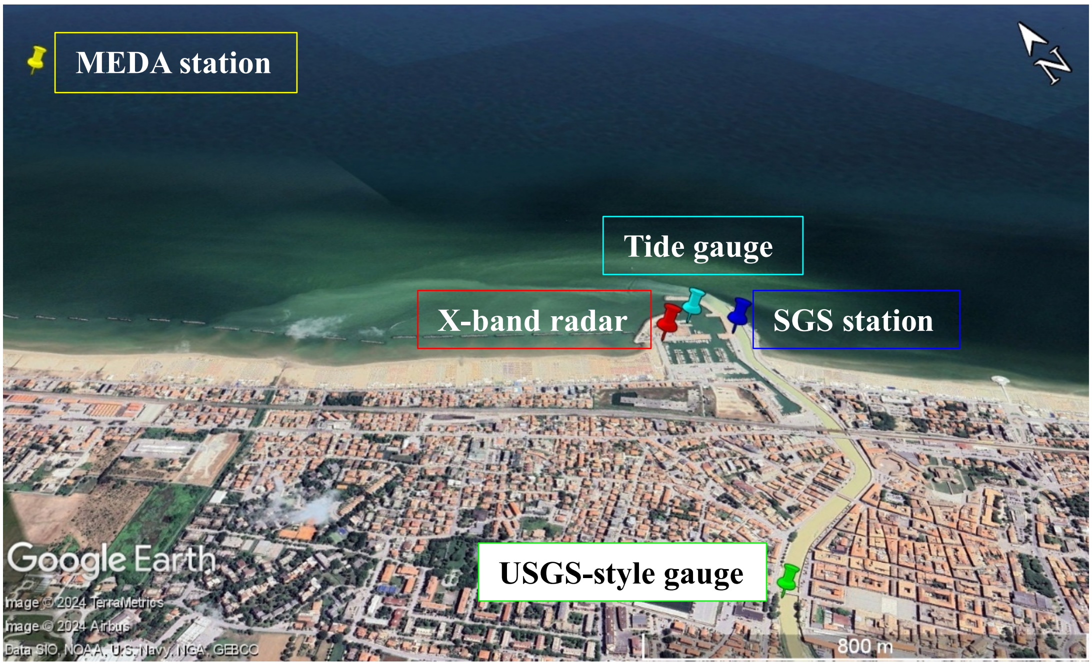

Figure 1. Instrumentation installed within and nearby the MR estuary.

Onsite sensors are also installed: an offshore ADCP, which collects the offshore wave characteristics (yellow pin); a tide gauge, which gather the water surface elevation in the Senigallia harbor (cyan pin); a stream gauge, collecting the water surface level and discharges in the MR, about 1 km upriver of the mouth (green pin). The whole instrumentation provides data that is continuously stored in a dedicated server. The available collected data, like the instantaneous tidal motion and offshore wave characteristics, are useful for the description of the UXO mobility and burial. In addition to existing research and datasets, the present field site offers unique characteristics, never taken into account in previous studies on UXO mobility and burial. Being it an estuarine environment, it is influenced by several forcing actions, with river current, sea waves and tidal motion being the main ones. Further, the bed soil is characterized by heterogeneous material, i.e. a mixture of sediments ranging from gravel to sand to silt to clay (Brocchini et al., 2017; Consorzio Di Bonifica Delle Marche, 2020). This means that a combination of cohesive, weakly cohesive and non-cohesive areas exists within the MR estuary and nearby nearshore (Figure 2; Table 1), this giving a complex scenario in terms of bed-morphology evolution and hydrodynamics. The sediment sorting and distribution are strongly affected by the environmental conditions and change very dynamically.

Materials and Methods

To meet the study objectives, we defined 7 tasks. The first task included the characterization of the hydro-morphodynamic of the MR estuary and the collection of UXOs. The second task encompassed the development of the experimental plan and the process of getting all the needed environmental compliance and permits to operate in the field. The writing of the Interim report closed Task 2. The third task consisted in running preliminary simulations of munitions behavior to get a first estimate of their possible migration and burial. Contracting for boat and diver support and purchase of the tracking system and acoustic system were included in task number four. Task 5 encompassed the field experiments and consequent data analysis. Taks 6 consisted in the validation of predictive models for UXO behavior, while Task 7 included the writing of the final report and scientific papers.

Figure 2. Sampling scheme of the sedimentological survey performed in 2019 (Consorzio di Bonifica delle Marche, 2020).

Letter	Sample	% gravel	% sand	% silt	% clay
A	1	<0.1	<0.1	55	45
	2	<0.1	<0.1	51	49
	3	<0.1	<0.1	48	52
B	1	<0.1	<0.1	51	49
	2	<0.1	<0.1	49	51
	3	<0.1	<0.1	56	44
C	1	<0.1	<0.1	62	38
	2	<0.1	<0.1	54	46
	3	<0.1	<0.1	55	45
D	1	<0.1	34	49	17
	2	<0.1	<0.1	58	42
	3	32	12	38	18
E	1	<0.1	58	34	8
	2	<0.1	42	48	10
	3	<0.1	9	65	26
F	1	69	30	0.7	0.4
	2	40	44	13	3.4
	3	26	71	2	0.9

Table 1. Overview of the results of the grain size analyses performed on the collected samples. Samples 1, 2 and 3 represent samples taken at different depth ranges: 0-0.5 m, 0.5-1 m and 1-2 m (Consorzio di Bonifica delle Marche, 2020).

Task 1 - Preliminary activities

Task 1.1 - Run Preliminary simulations of Misa River mouth hydro-morphodynamics

The MR belongs to a small-scale river basin (383 km^2) characterized by a torrential regime and large sediment transport. It originates from the Apennines and flows into the Middle Adriatic Sea after flowing through the coastal town of Senigallia (Marche, Italy). The river water discharges associated to return periods of 50, 100, 200 years are of about 505, 541, and 591 m^3/s, respectively[2]. The final stretch of the MR before reaching the mouth is highly engineered and monitored by the MORSE video-monitoring system (Figure 1). Despite its small size and moderate discharge, the MR distributes large quantities of sediment because of the ease of erodibility of the brittle and fractured rocks that constitute the Apennine Mountains. This leads to the formation of mouth bars, as in all Adriatic rivers, even with very different geometrical configurations and structural constraints. In fact, the MR mouth is located at the end of two concrete jetties, about 300 m seaward of the shoreline, this generating an artificial prodelta

[2]Regione Marche. Assetto di progetto media e bassa valle del fiume Misa. 2016. ElaboratoA.pdf (regione.marche.it)

region, unlike natural estuaries. Due to the reduced precipitation of the last years, the riverbed elevation has increased, leading to the emergence of an unusually large inner mouth bar (Figure 3). The evolution of such sediment deposit has been monitored through the SGS video-monitoring station and studied using the Delft3D numerical suite (Baldoni et al., 2021). The MR bed surface is mainly composed of silt and clays, with thick layers of muddy sediments and with percentage of sand and gravel increasing while approaching the river mouth (Table 1) (Brocchini et al., 2017; Consorzio Di Bonifica Delle Marche, 2020). The riverbed composition and the thicknesses of different sediment layers vary dynamically, depending on the environmental conditions.

Figure 3. Image of the MR inner mouth bar on November 24th 2023.

The coast of Senigallia is characterized by a very mildly sloping sandy beach, defended by breakwaters to the North of the MR estuary, while part of a natural open coast to the South. The coastline has a NW–SE orientation and faces approximately 40° from the North. The beach is characterized by medium ($D_{50} = 0.25 - 0.5$ mm) to fine ($D_{50} = 0.125 - 0.25$ mm) sand in its emerged portion and by fine sand in its submerged profile, with the sediment size decreasing moving toward the South (Postacchini et al., 2017). The coast of Senigallia is located in a micro-tidal environment, with maximum tidal excursion rarely exceeding 0.6 m (Mohamed et al., 2019)[3]. The two main wave regimes that characterized this area are induced by dominant and prevailing winds blowing on the Adriatic Sea, namely, Bora and Levante-Scirocco (Figure 4). The Bora is a cold NNE wind with a relatively short fetch since it flows along the minor axis of the narrow and elongated Adriatic basin. It generates short, steep and high waves that propagate almost perpendicular to the coast. On the contrary, the Levante-Scirocco is a warm wind that blows from ESE along the major axis of the Adriatic Sea, this resulting in a longer fetch and long and less steep waves coming from ESE. Due to wave refraction, the incoming direction changes to E in the nearshore area. These waves are typically associated with a large storm surge. These two wave regimes can occur during the same season; in general, the wintertime is characterized by severe storm events, while summertime has milder wave conditions. Both NNE and E waves can enter the river channel, but since the final stretch of the MR faces approximately 30° from the North, NNE waves penetrate more easily than E waves.

[3] RETE MAREOGRAFICA NAZIONALE - HOMEPAGE (mareografico.it)

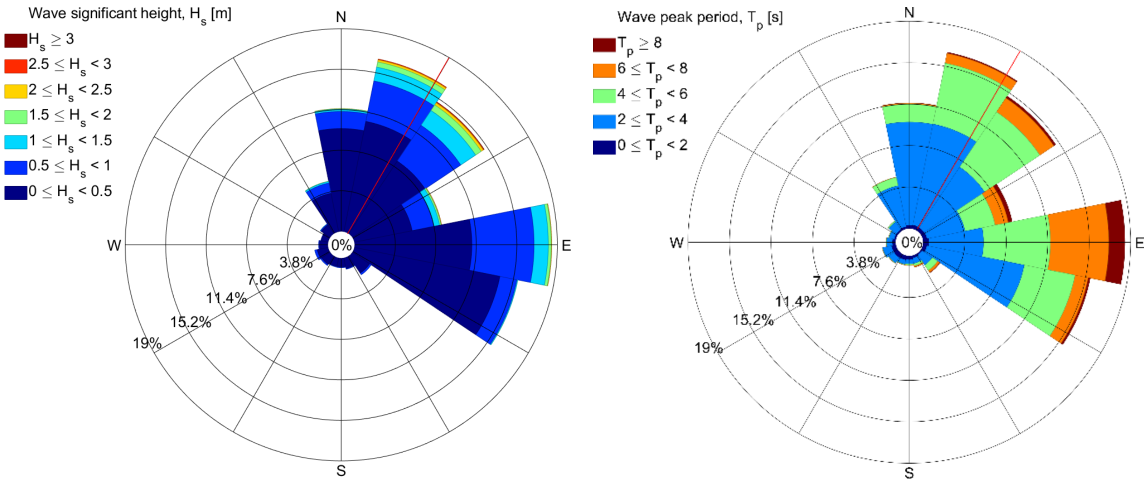

Figure 4. Wave rose for significant height and peak period. The red line identifies the orientation of the last stretch of the river, which is about 30°N. Wave roses refer to years 2000-2022. Data were obtained from the Reanalysis dataset of the MEDSEA_MULTIYEAR_WAV_006_012 of the Copernicus Marine Service, for the location 43.7708°, 13.2500° (around 6 km offshore of Senigallia).

The data collected by the existing, integrated monitoring system has already been used as inputs and benchmark for numerical models. Two-dimensional (2D) depth-averaged numerical simulations were run by means of the Delft3D software suite to study specific physical processes evolving at the mouth of the MR after some preliminary calibrations (Baldoni et al., 2021, 2022). The former of these works analyzed the evolution of the MR inner mouth bar under different forcing conditions. Specifically, the effect of the river discharges (R) and waves (W) were investigated. Two river discharge peaks of 50 m^3/s and 100 m^3/s, the latter comparable to the 1-year return period discharge, were tested with the wave process turned off. On the contrary, to observe the effects of the waves only, two significant wave height peaks were tested: 2m, a typical value for a storm interesting the Senigallia coast, and 5m, comparable to the 10-years return period wave height, computed from the observations of the National Wave Buoy Network[3]. The wave direction was chosen on the basis of the most frequent storms occurring at Senigallia, thus NNE (20°N) and E (90°N). Some simulations were run with and without adding a tidal forcing, to observe its effect on the bar dynamics. Results showed that river discharges cause downriver displacements of the bar crests, proportional to the discharge intensities, and sediment deposit downstream of the bar, suggesting downriver sediment transport. The waves push sediments upriver, causing the crest of the most seaward bar to grow and move upriver. As for the river discharge, also the displacement due to the wave action increases with the forcing strength. North-easterly waves, entering the estuary more easily, reach farther locations along the channel and modify the upriver portion of the deposit more than easterly waves. The tide has a minor influence on the bar evolution, with low tide causing the river current to speed up, thus triggering a larger erosion of the bar, while the opposite effect is determined by the high tide.

The above analysis reveals that the MR inner mouth bar has a dynamical evolution, mostly affected by the river discharge and the waves, while the tide only modulates the action of the two main forces. Moreover, the sediment expulsion out of the river mouth by the river discharge dominates over the upriver transport by the waves. In fact, river discharges comparable with the 1-year return period discharge induce downriver bar migrations much larger than the upriver displacements due to 10-years return period waves.

Some "river discharge only" and "wave only" simulations were also run using a modified bathymetry that better reproduces the present riverbed shape, with the bar located at the mouth (Figure 3). The results, shown in Figure 5, confirm that the bar evolves dynamically under the influence of the river discharge and waves, the former eroding the riverbed and causing downriver sediment transport, the latter pushing sediments into the mouth and triggering upriver bar migrations.

This scenario of dynamical evolution of the river mouth bar, was taken into due account during the definition of the experimental plan, the latter to be dynamically adapted in time in relation to the bar evolution and possible maintenance/dredging works carried out by the local authorities (i.e. Municipality, Marche Region Government, etc.).

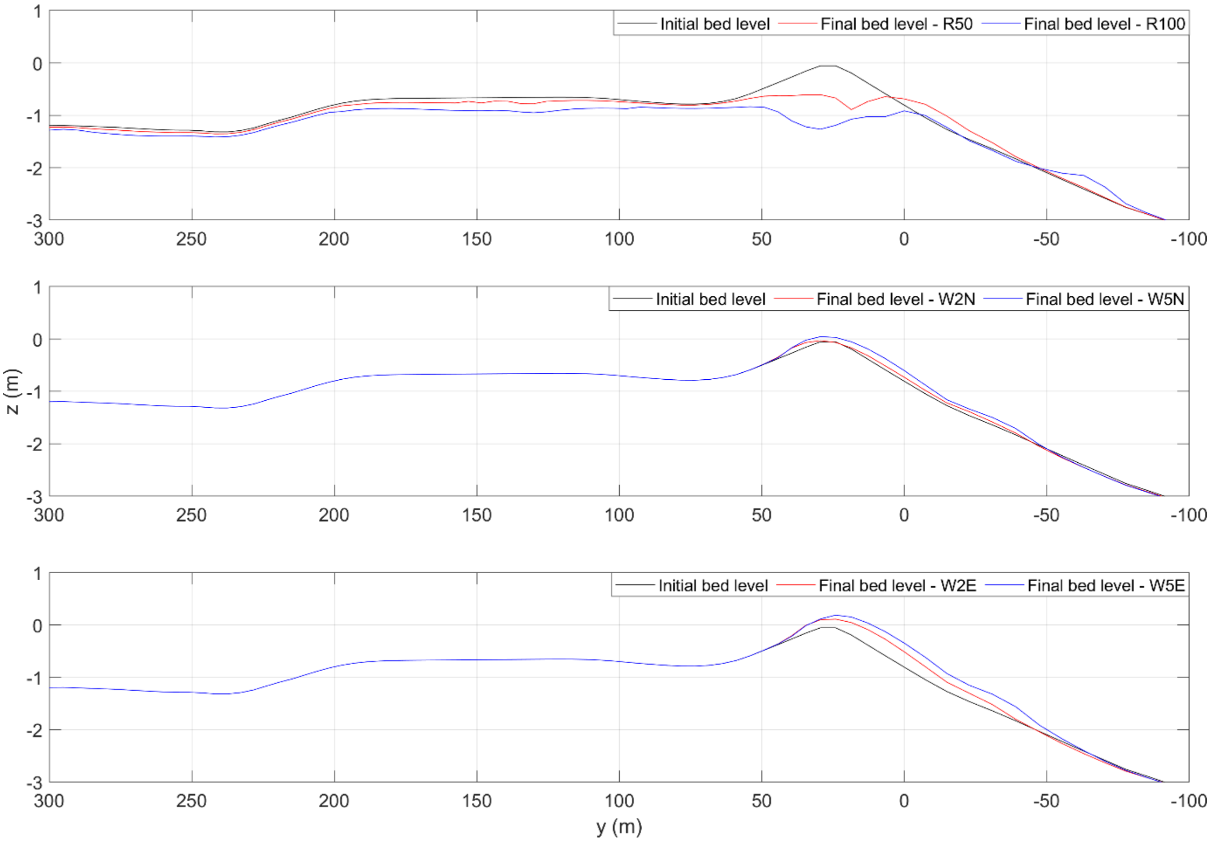

Figure 5. Results of the parametric simulations with the modified bathymetry (along river section; 0 represents the mouth, positive and negative values represent upriver and offshore locations, respectively). The top panel shows the evolution of the bed for discharge peaks of 50 m^3/s (red) and 100 m^3/s (blue), compared to the initial bed level (black). The middle and bottom panels show the evolution of the bed under NNE and E waves, respectively: the black line represents the initial bed level; the red and blue lines represent the final bed level for the simulations with 2 m and 5 m wave height, respectively.

Task 1.2 - Collect/build UXO surrogates

Run of the project experimental phase required the use of a number of munitions or surrogates, to be deployed and tracked in the field (MR mouth and nearby coastal area). After many interactions with both Project's partners and experts in the field, e.g. members of the US NRL (Stennis Space Center, Mississipi, USA) and of the NATO CMRE (La Spezia, Italy), it has been decided to follow two different routes to collect the needed objects: (1) to get as many as possible of them directly from the dedicated service of the Italian Army; (2) to get some simple cylinders built from a local blacksmith. In relation to point (1), we contacted the head of the "Stabilimento Militare Ripristini e Recuperi del Munizionamento" (Noceto, Parma) of the Italian Army, Colonel Luca Corrieri, and explained him our needs. We also agreed that the best solution was for us to go directly to the “Stabilimento” in Noceto to select and collect the UXO we thought useful. Therefore, on May 10th 2023 a group from our university (Prof. Maurizio Brocchini, Dr. Agnese Baldoni and the technician Mr. Livio Luccarini) collected the ammunitions at the “Stabilimento” (see Figure 6a). The meeting with Colonel Corrieri was very fruitful: beyond getting the UXOs we thought useful, we also received a great interest in our activities.

Figure 6. a) Professor Maurizio Brocchini and Colonel Luca Corrieri at the “Stabilimento Militare Ripristini e Recuperi del Munizionamento”; b) inert ammuntions painted in "Steel Blue"; c) steel cylinders built by a local blacksmith; d) 155mm projectile cut to place the instrumentation (grey cylinder in foreground) into it.

We collected a large number of inert (empty) ordnances (Figure 6b), namely:

- 3 pieces of US Projectile, 155mm HE, M107;
- 1 piece of US Cartridge, 105mm HEAT-T, M456, M456A1, M456E1;
- 3 pieces of US Cartridge, 105mm HE, M444;
- 4 pieces of 40mm L70 HE-PFF;
- 1 pieces of 120mm mortar round;
- 2 pieces of 60mm mortar round;

and received by Colonel Corrieri an accompanying certification of the UXOs be inert.

Ordnances have been painted in “Steel Blue” with a white “inert” mark on, to clearly highlight their inert nature (this being fundamental for them to be “accepted” during the field operations). Subsequently, following the specifications given by Colonel Corrieri, we filled the UXOs with mixtures of sand, gravel, iron and expanded polyethylene depending on the weight we had to achieve. Furthermore, one of the 155mm HE projectiles was cut in order to place sensors into it (see Figure 6d).

In relation to point (2), we got a local blacksmith build for us the following extra mock-up ordnances:

- 3 cylinders of 155mm;
- 1 cylinder of 120mm;
- 2 cylinders of 60mm.

as shown in Figure 6c. These were subjected to the same painting and filling procedure of the UXOs collected at the "Stabilimento".

Table 2 reports the main characteristics of the objects used in the field tests.

Table 2. Overview of the main characteristics of the objects used in the field experiments.

Object	Diameter [mm]	Length [mm]	Density [kg/dm^3]
	155	695	3.80
	105	495	3.11
	120	653	4.97
	60	240	2.64
	155	700	3.24
	60	250	2.03

Task 2 - Field experiment planning

Task 2.1 - Develop and write experimental plan

The experimental plan was for field experiments to be done in the period when most energetic sea and river conditions were expected, that is typically the fall-winter period. We planned to deploy UXOs at three different locations to observe different sea-river interactions:

1) along the final stretch of the river, where the river dominates;
2) at the river mouth, where the strongest sea-river interaction occurs;
3) offshore of the river mouth, where the sea prevails.

We initially planned to deploy at each location a number of objects (up to 5) in relation to expected events of significant sea forcing (sea storms), river discharges (intense rains) and mixed sea-river forced events. Forecast of the local weather and reading of local instruments guided the choice of the deployment period. A first trial was planned to be performed at the river mouth, which represents the most energetic location, to decide the final procedure to be used during the field tests. However, due to the presence of the mouth bar and the schedule of channel dredging operations (see Figure 7a), we performed the first test around 500 m upstream of the river mouth.

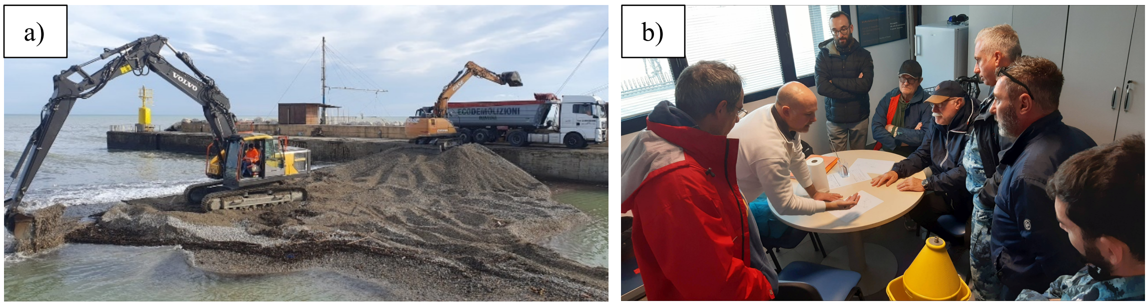

Figure 7. a) Dredging operations at the MR mouth; b) Meeting with the project working group.

The original work plan consisted of three phases. In the first phase, a diver would drop the UXOs on the seabed/riverbed and provide the zero-time position of each ordnance. In more details, the position of the heaviest UXO would be taken as reference (by using a picket and its GPS position), then the relative positions of the other ordnances would be taken by means of a graded rope and a compass. The diver's position would be given by means of a buoy equipped with a GPS. The objects would be tied, in series, to a reference anchor using a very slack rope. We believed this the right compromise between not losing the UXOs and let them free to move as much as possible. The second phase would consist in tracking the UXOs in time using two different systems, for two different timescales. For the first 5-6 hours of the experiment, when most of the motion is expected, using a receiver, the diver would follow the signal emitted by a pinger tied to the UXOs. The pinger would be attached with a rope and equipped with a floater to maintain the vertical position. Moreover, a buoy containing a GeoPoseModule (GPM), an intelligent tracking system (ITS) made of both a GPS and an AHRS modules, tied to the 155mm UXO, would be used to: 1) record data for estimating the UXO position; 2) be able to follow the UXO even if divers cannot get into the water due to adverse meteorological conditions. The third phase consists in the retrieval of the objects. Moreover, we also decided to cut one of the 155mm UXOs to be able to place one ITS inside the ordnance. Such configuration should give more precise measures of the UXO behavior (e.g., accelerations, angular velocity, tilt, roll) and give the opportunity to better understand how an embedded low-cost tracking system can be designed in the future. Section 4.2 contains the description of sensors and tracking systems.

The original plan was, then, modified in agreement with the working group (Figure 7b) after a series of fruitful meetings, including those with people expert in the field of munition response at the Department of Defense's (DoD) Energy and Environment Innovation Symposium. In the river, due to the available space (cross-section 25-35 m), 3 objects were deployed, while in the sea we limited ourselves to 4 pieces, to simplify the deployment and retrieval procedures. Since the diver had low-to-zero visibility underwater, particularly in the river, measuring the relative position of one object with respect to the others was impossible. Therefore, all position measurements were performed using the GPM. Since these measures had to be acquired at the surface, the diver, using a picket, fixed a buoy in correspondence with the object to be surveyed. Then, he resurfaced trying to stay aligned with the object vertical and performed the measurements. For the first two experiments, the ITS system was hand-carried by the diver, thus being submerged and re-emerging several times during the acquisition. This led to confuse and weakly reliable data. Therefore, we decided to tie the ITS on top of the buoy, so that it always remained out of the water, with a consequent improvement of the data accuracy. The position measurements were taken at the deployment and retrieval times and at intermediate times. A schematic representation of the experiment setup is shown in Figure 8.

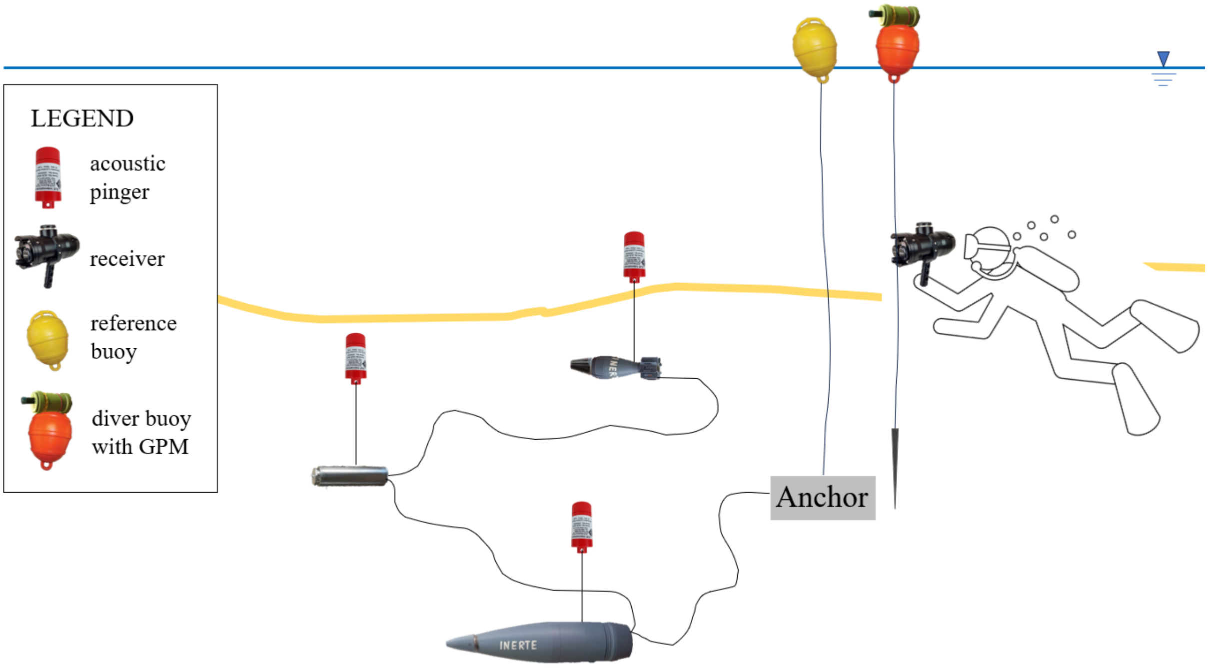

Figure 8. Sketch of the experimental setup.

To gain more information on the objects position, SOCOTEC Italia S.r.L performed some bathymetric surveys using an Autonomous Surface Vessel (ASV) CK-14 drone equipped with:

- a high-resolution MultiBeam system (Multibeam Norbit Technology);
- a DGPS/RTK positioning system with centimetric accuracy (Applanix WaveMaster);
- a compensation system for pitch, roll, yaw (Applanix WaveMaster);
- a software for data acquisition and processing.

Bathymetries of the study area 1) before the start of the experiments and 2) after the dredging operations are shown in Figure 9.

SOCOTEC also performed some Real-Time Kinematic (RTK) position measurements using a compact cable-free solution with Topcon's Vanguard technology, which provides an accuracy of 10mm + 1ppm for the horizontal coordinates. The sensor was located on top of an extendable rigid rod.

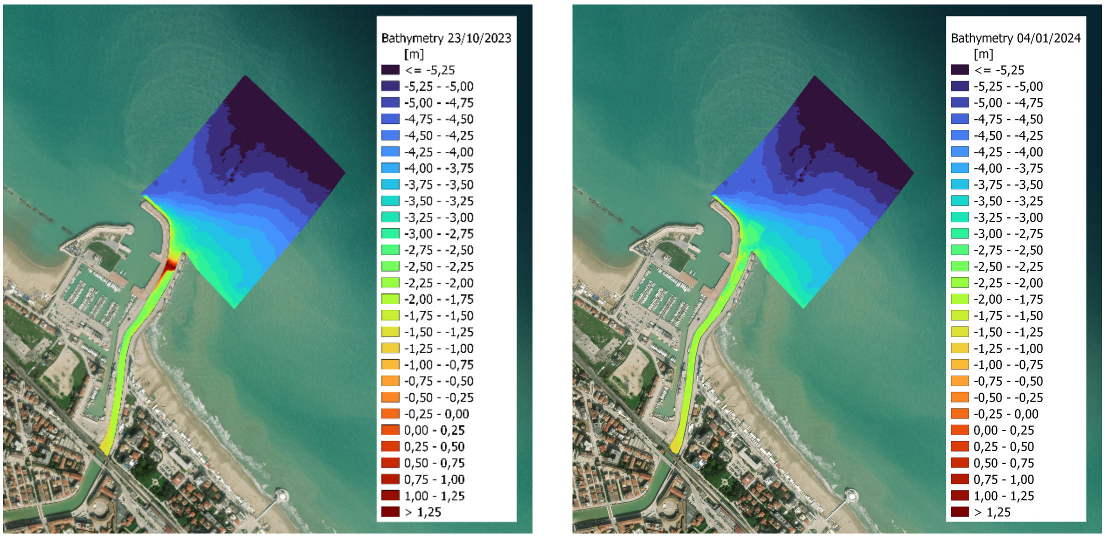

Figure 9. Bathymetries of the study area in October 2023 (left) and January 2024 (right), after the dredging of the mouth bar.

Task 2.2 - Environmental compliance and permits

To perform the field experiments programmed within the project, we contacted a number of institutions in relation to both work permits and interest in participation to the project. We asked for authorization from the Ancona Port Authority to execute the experiments in front of the MR mouth. They provided us with a clearance declaration specifying that: 1) the study area had to be marked with a light-emitting buoy (Figure 10a) and 2) that the navigation had to be prohibited during the experiments. They also promoted our studies to some Italian Navy services (e.g. diving and demining services); indeed, divers of the Ancona S.D.A.I. (Sminamento Difesa Anti Mezzi Insidiosi) of the Italian Navy supported us during the phase of UXOs retrieval (Figure 10c). We obtained clearance also from the Marche Region – Environmental and Hydraulic Resources Direction and from the Senigallia Municipality – Port Office to operate inside the final stretch of the MR and at the river mouth. In particular, the Senigallia Municipality asked us to provide suitable signages, to be located in the study area, to inform the population about the activities. We prepared four warning signs for the population, stating that the ordnances were inert and did not represent a danger to people and/or things (Figure 10b). There were no issues related to the environmental compliance. Finally, a joint security plan was prepared by the persons in charge of safety matters of our Department and Senigallia Servizi to perform the operations on the boat properly and safely.

Figure 10. a) The diver deploying the yellow light-emitting buoy to mark the area of the experiments; b) Warning sign; c) Some components of the Ancona S.D.A.I. of the Italian Navy with the divers of Senigallia Servizi and UNIVPM researchers.

Task 3-Numerical modeling – 1

Task 3.1 - Run and test of numerical model for UXO tracking

To better design our field experiments we run, with the help of the research groups of NRL-Stennis Space Center (leader Allison Penko) and Corvus Works UG (leader Peter Menzel), some preliminary tests of UXO burial and mobilization. In particular, we provided the environmental forcing conditions to NRL and Corvus Works, which run their burial/mobilization models.

The model developed by Corvus Works UG (MR21-1081), UXOmob, consists of both a mobilization module and a burial module, combined into one single software. The input data are delivered via csv-files that contain all environmental data, object data and wave information. Wave-induced current velocities, as well as background current velocity, are used by the mobilization module to derive the acceleration and, thus, the displacement of the object. If the object is not mobilized within the single wave cycle, the burial module is applied to compute a new burial depth. The behavior of a 155 HE projectile, for which Corvus Works had already a specification with corresponding drag, lift, and added mass coefficients, was simulated. The input parameters were the evolution of the bed level, the water depth and current field triggered by a river discharge event (100 m^3/s peak discharge) and the wave field produced by a wave storm (2 m peak wave height from NNE). The simulated time was two days, which is the typical duration of a flood event/wave storm in the MR environment. Moreover, the initial condition for the objects was of partial burial (20%, 50%, 70%, 100% with respect to the object diameter). A maximum burial depth and a mobilization indicator were calculated for each combination of environmental conditions and initial burial depth.

The work by NRL (MR-2733) consisted in developing a modeling system to nowcast and hindcast the underwater environment where munitions are found. Their aim was to couple Delft3D hydro-morphodynamic results to UnMES, a probabilistic model designed to estimate the mobility and burial of munitions (MR-2227). UnMES is a probabilistic Bayesian expert system that synthesizes databases of environmental conditions and recent research into physics-based process modeling of ammunition behavior in response to environmental forcing, with the goal of predicting the location of munitions and their degree of burial at underwater sites. UnMES includes modules for the dependence of scour burial on shear stress; the onset of motion in steady flow; the role of munitions density on burial and migration; the effects of oscillatory flow; the effects of the bottom flow direction; the acceleration effects on initiation of motion by the incorporation of an inertial factor for mobility threshold; the migration distance. The simulated forcing scenario was a combination of river discharge (100 m^3/s) and waves from NNE (2 m).

Input parameters for both UXOmob and UnMES were obtained from Delft3D simulations. A two-dimensional (2D) depth-averaged model was set up using three regular grids, rotated by 47.6° with respect to the North, to follow the coast orientation (Figure 11). The largest and the smallest grids (grid 1 and grid 3, respectively) were nested in the WAVE module, while the domain decomposition approach was used in the FLOW module between the intermediate-size grid (grid 2) and the smallest grid (grid 3). The largest grid covered the coastal area in front of the Senigallia harbor; it had a resolution of about 30 m and extended around 7 km in the alongshore direction and 2.5 km in the offshore direction. The intermediate-size grid was created from grid 1 by cutting some cells at the offshore and lateral boundaries. It extended about 6 km in the alongshore direction and 2.4 km in the cross-shore direction. The smallest grid covered the final stretch and the mouth of the MR and expanded about 1 km in alongshore direction and 1.5 km in the offshore direction. It had a variable resolution ranging from around

8 m in the offshore region to around 3 m along the river. The bathymetry was built out of a multibeam echosounder survey performed in 2020 and provided by the municipality of Senigallia. This dataset was integrated, to complete the bathymetry of the offshore region, with the values of the EMODnet bathymetry, available online (Figure 11). Three types of sediment were included in the simulations, one cohesive fraction and two non-cohesive fractions, namely sand and gravel. The median diameter of the sand was set to 180 µm, while the gravel was characterized by D_{50} =6 mm. The critical bed shear stress for the bedload transport initiation is around 0.05 N/m^2 and 0.06 N/m^2, respectively for sand and gravel. The cohesive fraction was characterized by a critical shear stress for erosion of 0.3 N/m^2, a critical shear stress for deposition of 0.4 N/m^2, a settling velocity of 0.1 mm/s and an erosion parameter of 10^{-4} kg/m^2/s. Such values fall within the ranges used in the literature (e.g., van der Wegen, 2010; Witting et al., 2010) and were chosen after a model calibration (see Baldoni et al., 2021; 2022). The percentages of cohesive sediment and sand were varied, respectively, by progressively increasing the sand fraction downstream of the most upriver section (in the following “river section”), located 600 m upriver from the mouth, where the bed was composed of cohesive sediment only, to the sea, where the bed was composed only of sand. In the final part of the river, in correspondence of the mouth bar, a 5% of gravel was added with an equivalent reduction of sand. The Delft3D FLOW and WAVE modules were online coupled to let currents and waves dynamically interact. At the two cross-shore boundaries of grid 2 a Neumann-type boundary condition of zero-water level gradient was imposed. A river discharge hydrograph was used to force the river section of grid 3. A timeseries of wave characteristics (significant wave height, peak period and direction) was imposed at the offshore boundary of grid 1.

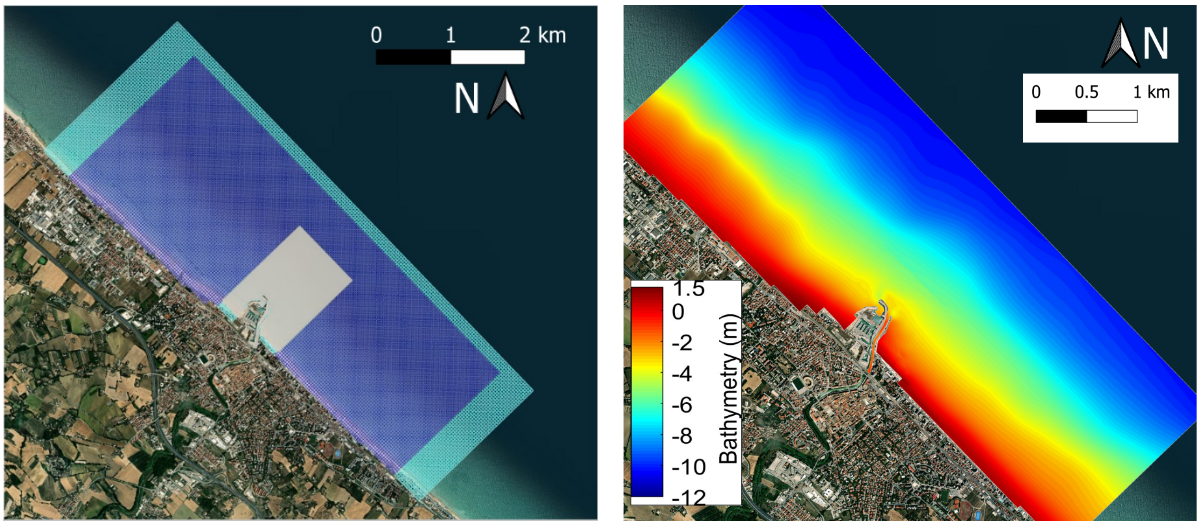

Figure 11. Left: Grids for Delft3D numerical simulations: grid 1 in cyan, grid 2 in blue, and grid 3 in gray. Right: Bathymetry used for the simulations.

According to Corvus Works’ interpretation of their simulations, reliable results could be found in the river area. For the simulated scenario (discharge peak of 100 m^3/s and a wave storm from NNE with a maximum wave height of 2 m), at the end of the event, a 155 HE projectile with an initial z_b/D=0.2 (z_b is the burial depth; D is the object diameter), would very likely bury in the river, with burial depth of 6cm, that correspond to z_b/D=40% (Figure 12a). The burial depth increases at the river mouth, exceeding 12cm in some areas. Figure 12b displays the mobilisation indicator: areas marked in red showed mobilisation during the simulation time, while transparent areas did not show any mobilisation. Results show that mobilisation could be expected just at the river mouth.

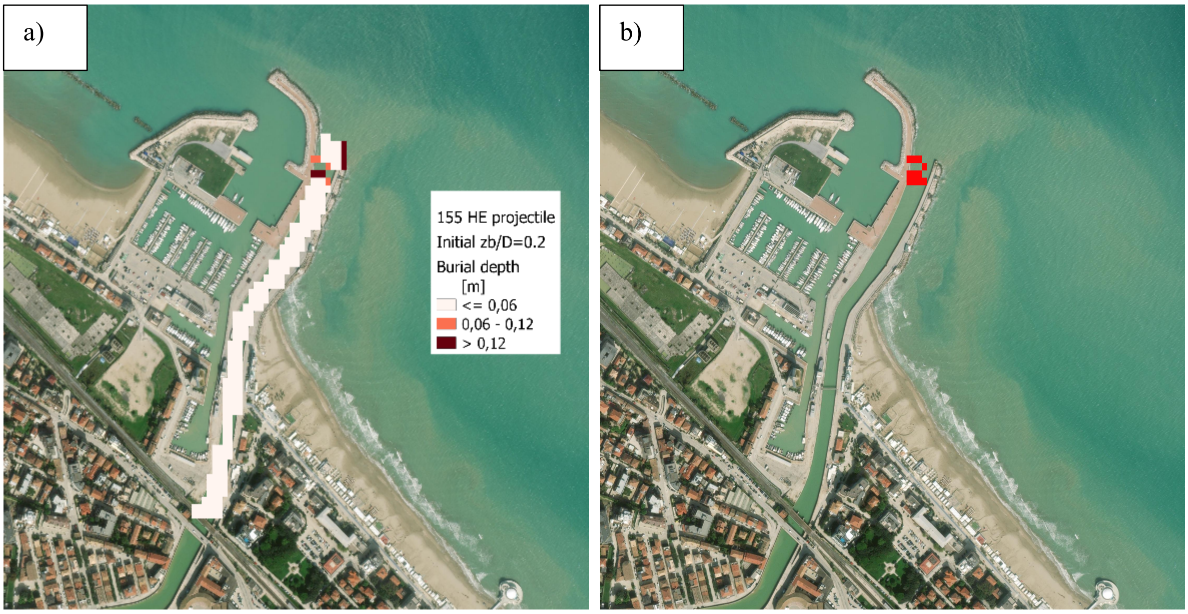

Figure 12. a) Maximum burial depth and b) mobilization indicator from Corvus Works' simulations.

NRL's results predicted, at the peak of the river discharge, complete burial along the river and 50% to 100% burial in the nearshore area (Figure 13a). A smaller burial was predicted in the offshore zone. The most probable migration distance was expected to be in the range of 0 m to 5 m (Figure 13b), longshore directed either towards SSE when objects are deployed North of the river mouth and offshore, or towards the onshore when objects are deployed in front of the river mouth and South of it and (Figure 13c).

Task 4 - Setup of field site

Task 4.1 - Contracting for boat and diver support

For the field experiments, we had the support of two different groups of divers. A diver of Senigallia Servizi, the company that manages the Senigallia harbor, supported us during the deployment and tracking of the UXOs. They provided us with a suitable boat to drop and retrieve all the heavy objects into/from the seabed. Moreover, the divers of the Ancona S.D.A.I. of the Italian Navy took part during the phase of UXOs retrieval, because of their expertise in the field. We had a meeting with the two groups of divers to coordinate the operations on September 27th. We planned to run a "simulation" of the field experiment in a pool before moving to the field, in order to:

- test the instrumentation for the tracking of the UXOs;
- understand the best way of doing other operations, such as the measurement of the relative distance between objects, as well as the communication between divers and people outside the water.

The "simulation" at the pool was performed on November 9th. During that occasion, divers of Senigallia Servizi, UNIVPM researchers and a member of the S.D.A.I. group were present. Both the pinger-receiver system and the GPM, described in the following section, were tested by divers (Figure 14a) showing a good performance.

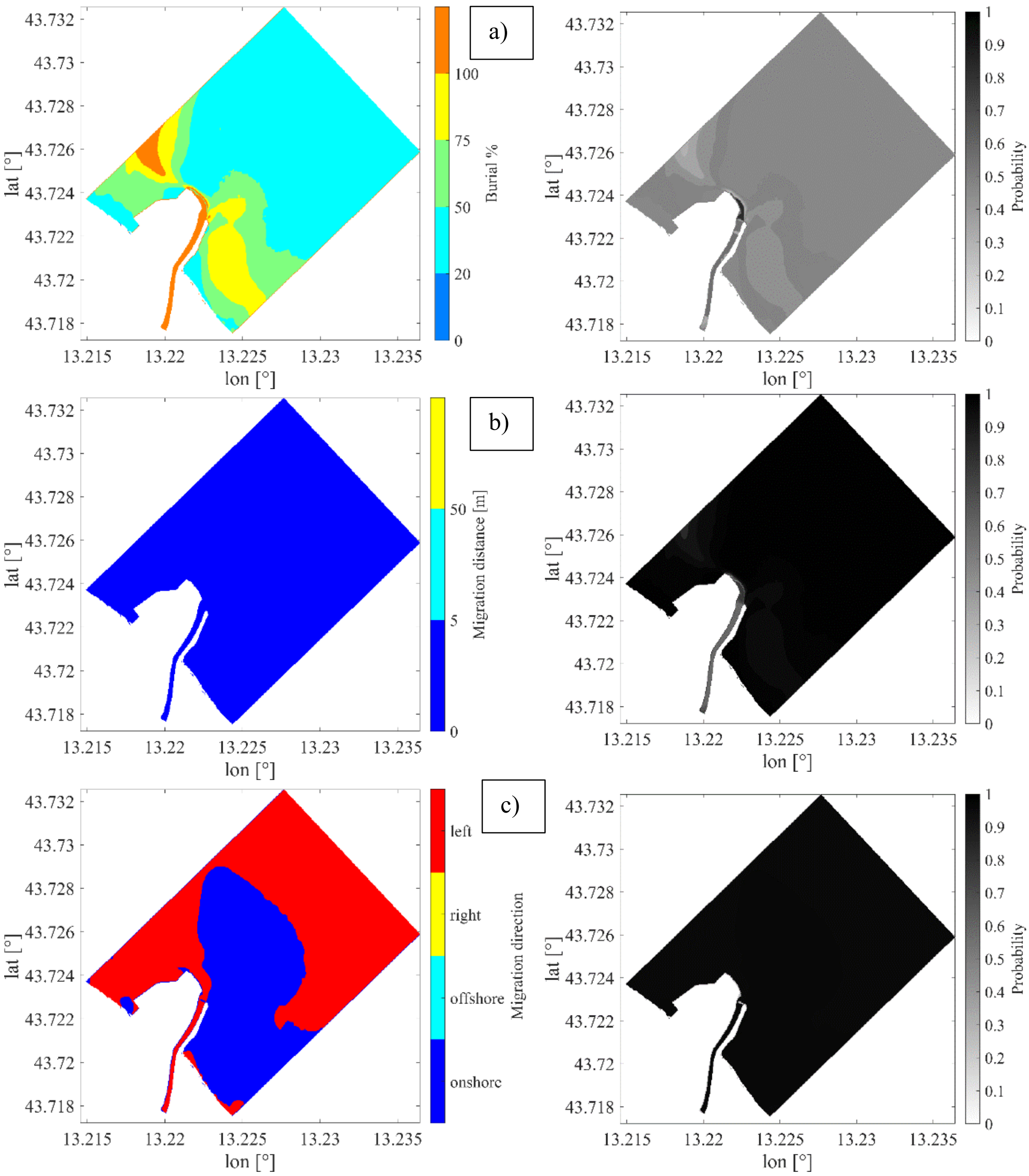

Figure 13. Results of NRL's simulation at the peak of the river discharge. On the left, most probable a) burial percentage relative to the object diameter; b) migration distance; c) migration direction. On the right, their respective probabilities of occurrence. Looking at the shoreline, left and right represent migration direction alongshore.

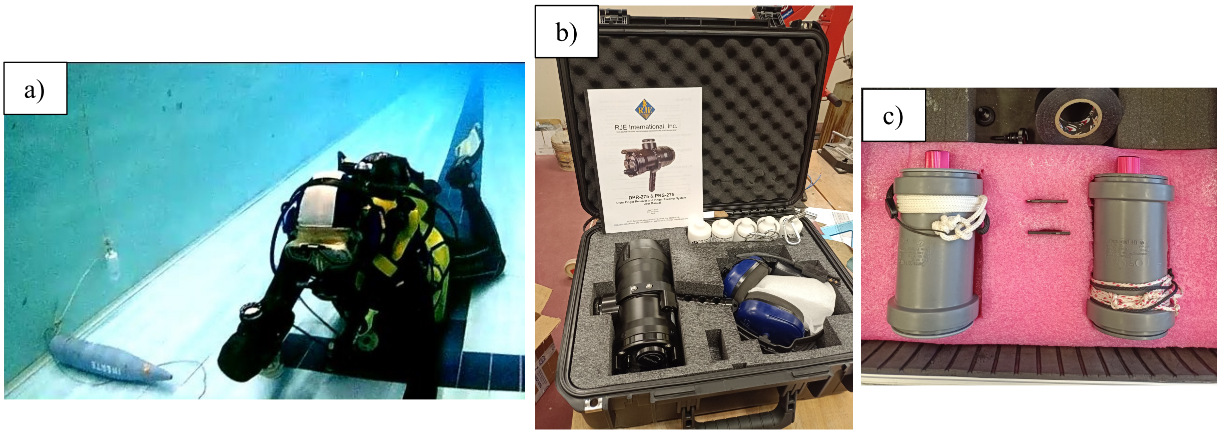

Figure 14. a) A diver testing the pinger-receiver system in the pool; b) pinger-receiver system; c) GPM1.

Task 4.2 - Purchase of electromagnetic UXO tracking system

To search and recovery UXOs from the seabed, we purchased a Diver/Asset Recovery System (DARS), consisting of an underwater pinger receiver and six acoustic pingers, produced by RJE International, Inc (Figure 14b). The pingers are water-activated and send an acoustic signal through the water that can be tracked and quickly located by a diver-held pinger receiver. Each pinger has a unique frequency (signature) that allows the diver to have an acoustic ID during the operation to assist in a quick recovery. The pinger is battery operated, uses an off-the-shelf 9-volt battery providing 30 days or more of operational life and is designed to be used by divers with a rugged and reliable design which requires little maintenance. To track and locate these pingers, the DARS system includes a state-of-the-art directional pinger receiver (DPR-275), which is diver-operated and easy to use, underwater headset and battery charger, six ULB-350 underwater location pingers with three different frequencies, 27, 37, 45 kHz. The equipment is supplied in a rugged waterproof shipping case for easy deployment. The DPR-275 is a battery-operated underwater acoustic signal receiver that detects the underwater acoustic pulse generated by a beacon in the range of 5 kHz to 80 kHz by means of a hydrophone attached to its housing. The incoming signal from the hydrophone is amplified by a tunable preamplifier, which is tracked with the local oscillator at a frequency difference of approximately 1.7 kHz. The mixer combines the two signals and amplifies the difference frequency, which is fed into the audio amplifier where additional gain is provided. The receiver is provided with a sensitivity control in order to prevent overload of the preamplifier at high signal levels. During the experiments, we tied the pingers to the objects deployed on the seabed. Following the manual indications, we mounted them vertically in the water column using some little floaters, with the end cap pointed down and the electronics module facing up.

The ITS technology was designed specifically for our experiments by the team of our colleague Prof. Eng. David Scaradozzi (UNIVPM-DII) and realized by the DII Spin-Off ANcybernetics. GeoPoseModule (GPM) is an “intelligent” pose-tracking platform supporting underwater object deployment and recovery. The GPM has been developed in two formats and for different experimenting phases: GPM1 is for logging the position of objects at a determined time at the sea surface of the local vertical (Figure 14c), and GPM2 is for monitoring an object motion from the deployment time until its retrieval. GPM implements a geolocation system that integrates an Inertial Measurement Unit (IMU) and a Mahony Orientation Filter to enhance vehicle orientation. In parallel, a data fusion system (based on an extended Kalman filter and a generic Fossen dynamic model of a submerged object) was developed to combine GPS and IMU data for accurate three-dimensional position estimation. Both GPMs are IMU/AHRS-based sensors that detect acceleration, angular velocity, angle, magnetic field, pressure, and GPS data. The robust housing and the small outline make them perfectly suitable for marine applications such as condition monitoring and predictive navigation. Configuring the devices enables addressing various applications by interpreting the sensor data by smart algorithms and Kalman filtering. The main differences between GPM1 and GPM2 are the battery capacities and the IMU accuracy. GPM1 was tested and verified at the swimming pool and in a real environment (river) compared to Garmin GPS73 surface GPS logs; GPM2 was not calibrated due to lack of time. A Matlab code allows one to visualize the GPM recordings in real-time through a WiFi connection so that the user can check the correct functioning of the instrument and the quality of the GPS signal. The characteristics of the GPMs are listed in Appendix A.

Task 5 - Field tests

Task 5.1 - Field deployment of surrogates and tracking

The experimental campaign started on November 17th and lasted around 3 months. We performed a total of 5 UXOs deployments: 3 in the river, 1 in the sea and 1 at the river mouth. The left panel of Figure 15 shows the areas where the field tests were performed. Each test consisted of three different phases: field deployment, intermediate measurements and retrieval. The general procedure is that described in Task 2.1. However, some changes occurred depending on the availability of the divers of the Italian Navy and of SOCOTEC Italia S.r.L.

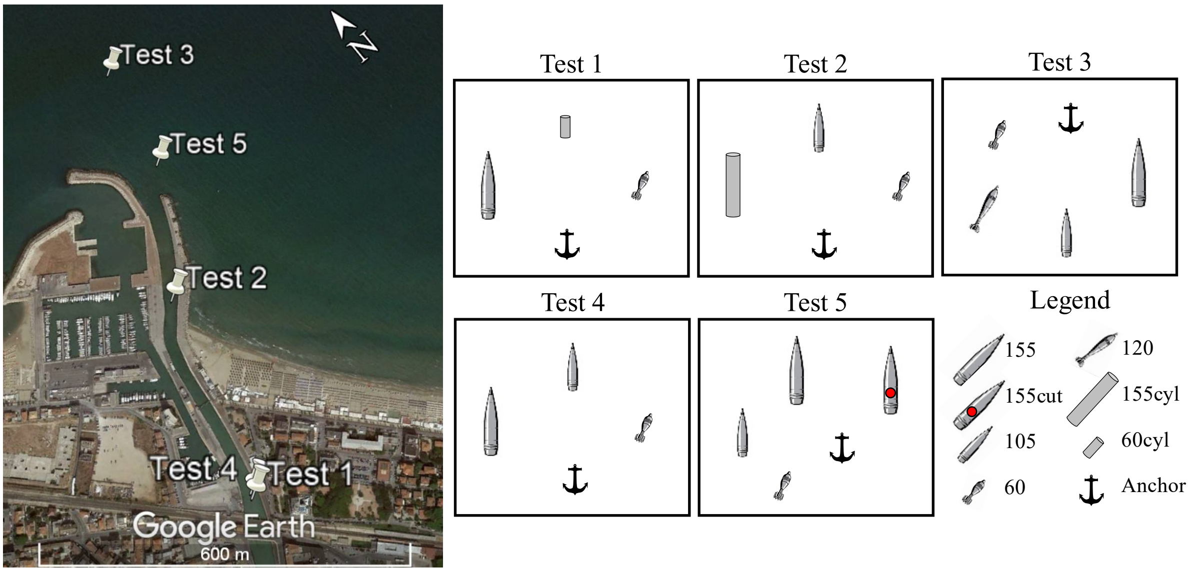

Figure 15. Left: Areas where the 5 field experiments were performed. Right: schemes of the object deployment for each test.

Right panels in Figure 15 show the deployment scheme for each experiment:

- Test 1: 155mm HE projectile, 60mm cylinder, 60mm mortar round;
- Test 2: 155mm cylinder, 105mm HE projectile, 60mm mortar round;
- Test 3: 155mm HE projectile, 105mm HE projectile, 120mm mortar round, 60mm mortar round;
- Test 4: 155mm HE projectile, 105mm HE projectile, 60mm mortar round;
- Test 5: 155mm HE projectile, 155mm HE cut projectile, 105mm HE projectile, 60mm mortar round.

Test 4 was performed at the same location as Test 1 because, since Test 1 was a first trial, we considered that measures were not very reliable and repeating the experiment a second time would have been appropriate. The only difference was that we replaced the 60mm cylinder with the 105mm UXO.

The water depth in the river for Tests 1 and 4, at the deployment time, was around 1.85m and 1.65m, respectively, with a mud layer of about 50 cm. In Test 2, the water depth was around 2m, with a mud layer of 70cm. The objects were deployed at around 6m apart, due to the limited space available within the river cross-section, with the object heads oriented upriver. The riverbed was characterized by the presence of sparse gravel spots.

Tests 3 and 5 were performed at a water depth of around 5m and 2.8m, respectively, and the initial distance among objects was of about 5-9m. While the seabed in Test 3 was completely sandy, in Test 5 some gravel appeared close to the river mouth, in correspondence with the 60mm mortar bomb.

For all the experiments, objects were connected by ropes, each one being 27m long.

Table 3 reports the schedule of each test. SOCOTEC Italia S.r.L executed MultiBeam surveys on November 21st and 30th, December 20th and 27th, January 4th and 5th. In December (20th and 27th) and January (4th and 5th), they also performed position measurements.

Table 3. Schedule of field experiments.

	Deployment	Intermediate measures		Retrieval
Test 1	November 17th	November 21st		November 24th
Test 2	November 24th	December 1st		December 5th
Test 3	December 20th	December 27th	January 5th	January 17th
Test 4	January 4th	January 12th		February 2nd
Test 5	January 31st	-		February 6th

The Italian Navy supported us during the retrieval phase for Tests 1 and 2.

Task 5.2 - Data analysis

The types of data we collected are:

- GPM measurements;
- SOCOTEC measurements;
- SOCOTEC MultiBeam surveys;
- Burial measurements.

Only GPM measurements required post-processing by UNIVPM. Two types of analyses were performed for GPM1 and GPM2.

GPM1 was used by the diver to measure UXOs position. The acquisition frequency was of 2Hz and the system acquired continuously from ignition, so that the entire diver's route was saved. Through the mentioned Matlab script, a user located out of the water could visualize the data in real-time. Every time the diver reached an object, he closed and re-opened the GPM cap. By doing this, a new line was written in the Matlab Command Window and in the output Excel file, indicating the start of a new recording. After 15 seconds, the end of the recording was reported; then, the diver proceeded to the following object. An example of Excel spreadsheet is shown in Figure 16.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	N Reg	Time	ax	ay	az	gx	gy	gz	mx	my	mz	lon	lat	SN	PDOP	HDOP	VDOP	q0	q1	q2	q3
4659	3	2670.02	-0.14	-0.22	-0.93	-0.18	-26.55	-30.15	-5480	-167	9538	131341728	434351232	22	1	0.6	0.8	0.16	-0.9	0.4	-0.03
4660	3	2670.53	-0.01	-0.3	-0.96	5.74	10.93	-3.91	-5101	-56	9709	131341736	434351232	22	1	0.6	0.8	0.19	-0.9	0.38	-0.05
4661	3	2671.03	-0.07	-0.31	-0.95	8.36	-13.24	-11.84	-4693	-143	9818	131341736	434351232	22	1	0.6	0.8	0.19	-0.91	0.36	-0.04
4662	3	2671.55	0.02	-0.35	-0.93	-30.94	-4.39	-5.19	-3543	-356	9903	131341744	434351232	22	1	0.6	0.8	0.21	-0.91	0.35	0.01
4663	3	2672.06	-0.59	-0.17	-0.98	12.63	14.16	18.01	-3733	-547	9897	131341744	434351232	22	1	0.6	0.8	0.19	-0.91	0.36	-0.01
4664	Avvio registrazione numero 4																				
4665																					
4666	4	2672.59	-0.17	-0.36	-1.04	-31.25	-24.35	-12.51	-2615	-1081	9728	131341744	434351232	22	1	0.6	0.8	0.19	-0.93	0.32	0.05
4667	4	2673.1	-0.19	-0.33	-0.9	0.98	-4.03	22.77	-2114	-1217	9612	131341744	434351232	22	1	0.6	0.8	0.18	-0.92	0.34	0.07
4668	4	2673.61	-0.28	-0.26	-0.93	-4.09	-10.68	-10.19	-2270	-1337	9607	131341752	434351232	22	1	0.6	0.8	0.17	-0.91	0.36	0.07
4669	4	2674.12	-0.2	-0.24	-0.96	1.59	2.93	-8.24	-2378	-1281	9667	131341752	434351232	22	1	0.6	0.8	0.17	-0.91	0.38	0.06
4670	4	2674.62	-0.26	-0.25	-0.91	5.07	2.99	3.11	-2553	-1365	9685	131341752	434351232	22	1	0.6	0.8	0.16	-0.9	0.39	0.05
4671	4	2675.13	-0.22	-0.33	-0.94	1.95	-5.62	-7.45	-2557	-1302	9655	131341760	434351232	22	1	0.6	0.8	0.17	-0.91	0.38	0.04
4672	4	2675.64	-0.2	-0.24	-0.93	4.33	8.54	6.96	-2510	-1190	9723	131341760	434351232	22	1	0.6	0.8	0.17	-0.9	0.39	0.03
4673	4	2676.15	-0.32	-0.35	-0.94	-18.25	1.16	-14.65	-2231	-1529	9524	131341760	434351232	22	1	0.6	0.8	0.15	-0.92	0.36	0.04
4674	4	2676.66	-0.33	-0.17	-0.94	-13.12	2.56	-12.63	-2098	-1410	9583	131341760	434351232	22	1	0.6	0.8	0.17	-0.92	0.36	0.03
4675	4	2677.16	-0.07	-0.3	-0.99	16.66	13.12	-2.32	-3399	-1033	9786	131341760	434351232	22	1	0.6	0.8	0.16	-0.9	0.4	-0.04
4676	4	2677.67	-0.11	-0.38	-0.89	12.76	-6.41	-8.24	-4123	-536	9833	131341768	434351232	22	1	0.6	0.8	0.18	-0.89	0.42	-0.07
4677	4	2678.18	0.15	-0.38	-1.05	-9.03	-9.89	-15.99	-2890	-806	9841	131341768	434351232	22	1	0.6	0.8	0.19	-0.93	0.31	0.01
4678	4	2678.69	-0.01	-0.57	-0.84	28.56	32.04	-51.88	-2243	690	9653	131341768	434351232	22	1	0.6	0.8	0.28	-0.95	0.12	-0.07
4679	4	2679.19	-0.14	-0.61	-0.61	7.14	-20.02	-107.97	-686	1255	8785	131341768	434351232	22	1	0.6	0.8	0.33	-0.94	0.02	-0.01
4680	4	2679.7	0.07	-0.73	-0.75	-91.31	-10.93	23.32	-1347	1426	9036	131341768	434351232	22	1	0.6	0.8	0.17	-0.98	0.08	0.07
4681	4	2680.21	-0.26	-0.33	-0.94	-4.39	-13.98	-45.65	947	-159	8055	131341776	434351232	22	1	0.6	0.8	0.19	-0.98	0	0.1
4682	4	2680.72	-0.26	-0.68	-0.9	35.95	39.92	85.75	227	727	8403	131341776	434351232	22	1	0.6	0.8	0.32	-0.94	0.13	0.05
4683	4	2681.22	-0.15	-0.89	-0.68	-15.08	23.07	66.28	867	913	7685	131341776	434351232	22	1	0.6	0.8	0.24	-0.97	-0.02	0.08
4684	4	2681.73	-0.2	-0.04	-1.01	42.3	13.43	0.18	902	98	7938	131341784	434351232	22	1	0.6	0.8	0.22	-0.97	0.01	0.08
4685	4	2682.24	-0.12	-0.35	-0.95	3.36	-3.97	4.15	1018	192	7836	131341784	434351232	22	1	0.6	0.8	0.22	-0.97	0.01	0.08
4686	4	2682.75	0.04	-0.27	-1.02	5.13	31.01	-5.37	621	551	8161	131341792	434351232	22	1	0.6	0.8	0.21	-0.98	-0.04	0.04
4687	4	2683.25	-0.23	-0.49	-0.94	-23.07	-7.57	-10.31	1316	536	7443	131341792	434351232	22	1	0.6	0.8	0.18	-0.98	-0.07	0.08
4688	4	2683.76	-0.15	-0.49	-0.95	2.44	-6.53	-40.77	1146	680	7590	131341792	434351232	22	1	0.6	0.8	0.2	-0.98	-0.07	0.06
4689	4	2684.27	-0.21	-0.58	-0.78	-8.97	-18.19	0	1347	624	7413	131341792	434351232	22	1	0.6	0.8	0.18	-0.98	-0.08	0.09
4690	4	2684.77	-0.15	-0.56	-0.91	16.36	-4.21	-20.69	1377	1066	7125	131341800	434351232	22	1	0.6	0.8	0.21	-0.97	-0.13	0.09
4691	4	2685.28	-0.19	-0.49	-0.94	-6.04	-11.84	-25.94	1441	1659	6699	131341800	434351232	22	1	0.6	0.8	0.2	-0.95	-0.19	0.1
4692	4	2685.79	-0.12	-0.3	-0.94	13.85	-9.52	18.31	1583	1704	6491	131341800	434351232	22	1	0.6	0.8	0.19	-0.94	-0.24	0.12
4693	4	2686.3	-0.26	-0.39	-0.95	10.07	21.36	10.19	1239	1904	6720	131341808	434351232	22	1	0.6	0.8	0.24	-0.95	-0.18	0.08
4694	4	2686.81	0.05	-0.44	-1.06	-3.54	-16.54	6.47	874	2156	6953	131341808	434351232	22	1	0.6	0.8	0.24	-0.94	-0.22	0.09
4695	4	2687.31	-0.19	-0.66	-0.87	3.72	-16.72	-24.6	1359	2629	5821	131341808	434351232	22	1	0.6	0.8	0.28	-0.93	-0.21	0.12
4696																					
4697	Fine registrazione numero 4																				

Figure 16. Excel spreadsheet excerpt.

Columns A to U contain:

- the ID number of the recording;
- the time from ignition [s];
- accelerations in x, y, z [m/s^2];
- angular velocities around x, y, z [rad/s];
- magnetic field intensity in x, y, z [μT];
- longitude and latitude (DMM);
- SN (Satellite Number), which indicates the number of available GPS satellites;
- PDOP (Positional Dilution Of Precision), HDOP (Horizontal Dilution Of Precision), VDOP (Vertical Dilution Of Precision), which represent the accuracy of the GPS measures;
- quaternion components (q0, q1, q2, q3), which represent the orientation of the object in a 3D-space.

In post-processing, only data associated with a good signal, that is a good PDOP (<4), were analyzed. PDOP is a parameter used to describe the strength of the current satellite configuration, or geometry, and its impact on the accuracy of the data collected by a GPS receiver at the time of use (measure of accuracy in 3-D position). Low PDOP values, in the range of 4.0 or less, indicate good satellite geometry, whereas a PDOP greater than 7.0 indicates that the satellite geometry is weak and, therefore, the user should not rely on the accuracy of that data and should wait until a better PDOP value could be attained by the satellites moving into preferable positioning in the sky. First, the WGS84 coordinates were projected into UTM33N. Then, the mean of the recorded data for each recording gave the position of each object, while the variance indicated the data scattering. In most cases, the variance was of the order of centimeters or less, meaning that the diver remained quite still while measuring.

However, another error needs to be considered in the analyses, that is the incorrect positioning of the diver on the exact vertical of the object. Such error increases with the water depth, therefore particular attention was paid to the measurements performed in the sea.

To help us understand and improve the accuracy of the results, we could rely on:

- the known distances between the objects at the deployment time;
- some high-resolution (10 cm) MultiBeam surveys performed by SOCOTEC Italia S.r.L;
- some position measurements performed by SOCOTEC Italia S.r.L;
- video and photo report.

Moreover, the object behavior was interpreted on the basis of the forcing actions occurring on the period of the experiments. Data were obtained by both the MORSE monitoring system[4] and other instrumentation, depending on their functioning during the investigated period. For the wave climate data, we used:

- MORSE X-band radar (Figure 1), which provides reliable data above a certain threshold for Hs (around 0.8m);
- Ancona wave buoy, placed at 70m water depth (43° 49' 26"N, 13° 43' 10"E)[5], managed by the Italian Institute for Environmental Protection and Research (ISPRA);
- Fano ADCP, located at 12m water depth (43° 53' 30"N, 13° 00' 30"E)[6], managed by the National Research Council – Institute of Marine Biological Resources and Biotechnologies (CNR IRBIM).

Data of river water level were obtained both by a hydrometer managed by the Civil Protection of the Marche Region and by the MORSE USGS-style gauge (Figure 1), which provides reliable data only when it is submerged. Both instruments are installed around 1 km upstream of the river mouth. The USGS-style station also provides the velocity inside the river and, consequently, the river discharge. Sea water levels (here called tide) were derived from the MORSE tide gauge located in the harbor of Senigallia. Images and videos acquired by the SGS station were also useful to inspect the environmental conditions at the estuary (Figure 1).

GPM2 was placed inside the cut 155mm HE projectile and acquired 1 datum per second, for 7 consecutive days (Figure 17a and b) and saved them in an Excel spreadsheet. During the post-processing phase, performed in the Matlab environment, some anomalous spikes were observed and filtered out. Subsequently, Euler's angles were extracted form the quaternions and plotted, together with the accelerations, for each day of the experiment.

Task 6-Numerical modeling – 2

Task 6.1 - Validation of UXO-tracking numerical model and predictions

A Delft3D numerical simulation of Test 3 was performed, using the setting described in Task 3.1, to obtain input parameters to feed UnMES. The simulated period was December 20th to January 17th. Since Test 3 was performed in the sea, just one sediment type was considered, namely sand (D_{50}=0.18mm), to decrease the computational time. Therefore, simulation results in the river were discarded. Probabilistic results for burial depth and migration distance of a 155mm projectile were then compared to observed ones (see Test 3 in the Result and Discussion section).

[4] Morse (univpm.it)
[5] stazioni (mareografico.it)
[6] FANO – IRBIM (cnr.it)

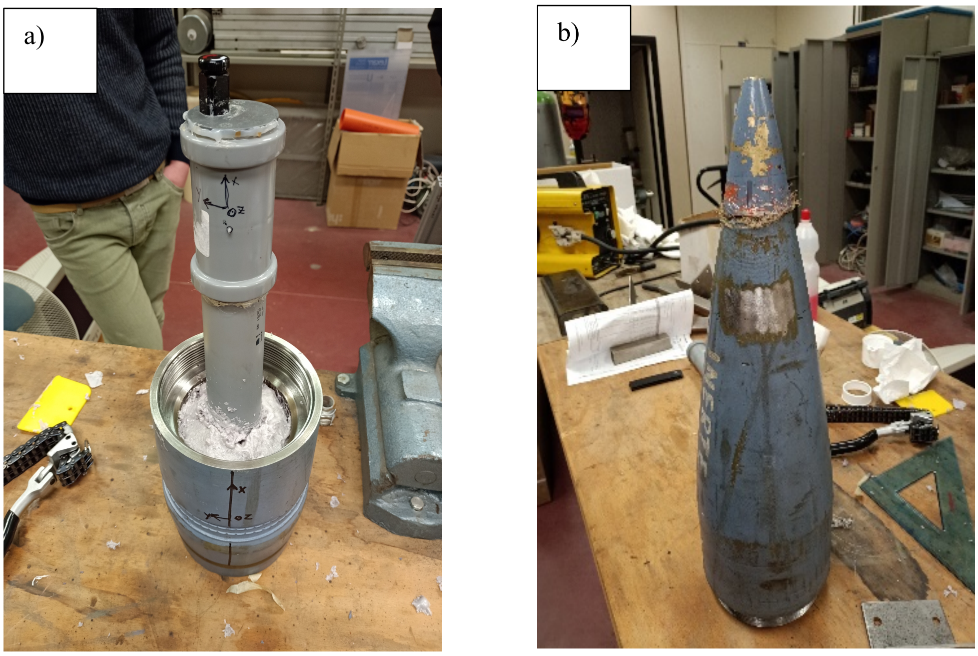

Figure 17. a) GPM2 fixed inside the 155mm projectile base; b) 155mm projectile upper part.

Task 7-Reporting and papers

Task 7.1 - Prepare and submit final report and scientific papers

Professor Maurizio Brocchini and the post-doctoral fellow Agnese Baldoni participate to Department of Defense's (DoD) Energy and Environment Innovation Symposium, which took place in Arlington, Virginia from November 28th to December 1st, 2023, where they presented a poster with the developments of the MINELAB project.

A detailed summary of the work done during the project is exposed in this report and will be presented on May 22nd at the 2024 Munition Response Spring In Progress Review.

An oral presentation on “Munitions mobility and burial in a micro-tidal estuary” will be given at the 38th International Conference on Coastal Engineering that will be held in Rome, September 8th – 14th 2024, and a scientific paper is also under preparation.

Results and Discussion

Test 1

Test 1 represents our first trial in the field. On November 17th, the objects were dropped from the water surface 500 m upstream of the river mouth, as shown in Figure 18a. During this experiment, the diver held the GPM bounded to his hand, thus submerging it while going underwater. This probably caused a not perfect functioning, confirmed by a diver’s measured route that not always corresponded to the real one. Object positioning was, therefore, estimated combining measurements, MultiBeam survey (Figure 18b), photo and video recordings. Since the survey was carried out when the smallest objects were completely buried, only the anchor is recognizable from it.

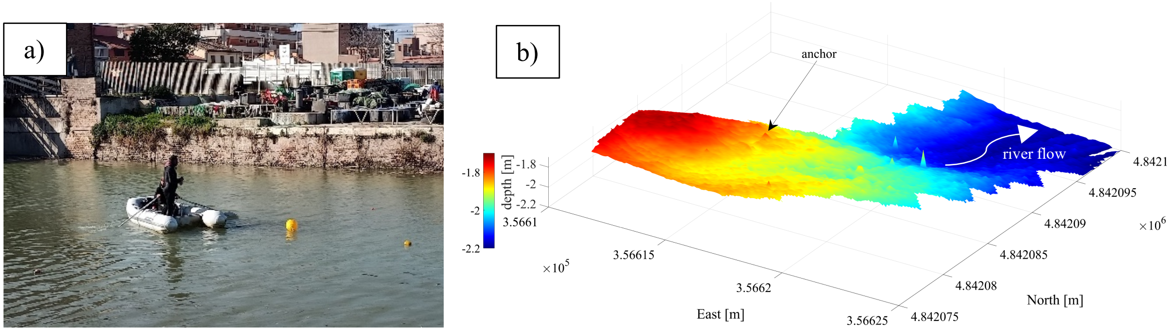

Figure 18. a) Deployment of the objects (red circles) on November 17th (left bank of the river visible); b) 3D-view of the MultiBeam survey performed on November 21st.

Results of Test 1 are shown in Figure 19 and reported in Table 4. The 155mm HE projectile was found head-down plunged into the mud layer and, therefore, it is very unlikely that it moved. A similar behavior was observed by Donohue & Garrison (1954) and McMaster et al. (1955): a mine, dropped from the water surface in a clayey-silt mud bottom, struck the bottom nose down, and the force of impact imbedded about one half of the mine's bulk in the bottom mud; the mine remained in the initial position with little modification.

The smallest objects were also found buried, but they experienced a downriver migration and, subsequently, they moved upstream. The 60mm mortar bomb showed the maximum mobility and, at the retrieval time, it resurfaced on a gravel spot.

Before November 21st, neither significant wave-driven events occurred, nor strong river flows (Figure 20), therefore the downstream displacements observed for the 60mm objects were probably due to the sloping bathymetry.

A sea storm occurred between November 21st and November 23rd, with an offshore (in 70 m water depth) significant wave height of about 3 m, coming from the NNE, thus oriented perpendicularly to the estuary. Data of our X-band radar (red dots in Figure 20, left) agreed with the Ancona Buoy (in blue), just showing a smaller wave-height distribution because it refers to a shallower area (i.e. less than 12m).

Precipitations also occurred on November 21st and 22nd, causing an increase of the river water level, but no significant river flows (our river gauge recorded a maximum speed of 20 cm/s), due to both the simultaneous sea action and the presence of the bar at the river mouth. On the evening of November 21st, an opening formed in the leftmost portion of the mouth bar, caused an abrupt decrease of the river water level, letting sea water enter the estuary, with the tide propagating up to the river gauge location (around 1 km upstream of the mouth). Wave propagation inside the river channel might have triggered the upriver migration of the objects.

Richardson et al. (2001) observed that objects of sufficient density, whose buoyant weight exceeds the bearing capacity of the cohesive sediment bed, may sink into the sediment. Such behavior was observed in no storm-conditions (Inman & Jenkins, 2002; MR-2730), while a much larger burial was detected during storm conditions (MR-2730), when the water content of the mud layer increases with consequent decrease of the sediment bulk density (Sahin et al., 2012). Inman & Jenkins (2002) also suggested that burial does not exclude migration because, during storms, both the mine and muddy bed may move as a unit.

The role of sediment type and sorting also seemed to play a role in the UXO behavior, since the 60mm mortar bomb resurfaced in correspondence of a gravel spot.

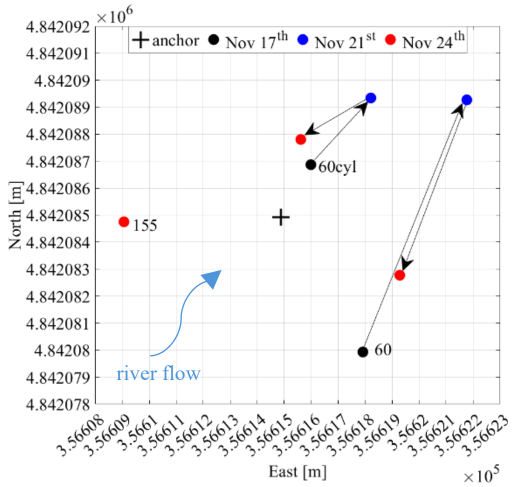

Figure 19. Object positions during Test 1.

Table 4. Object migration distances and burials in Test 1.

Object	November 21st		November 24th	
	M [m]	B [cm]	M [m]	B [cm]
155	-	50	-	50
60 cyl	3.3	31	3.0	23
60	10.1	46	6.9	-

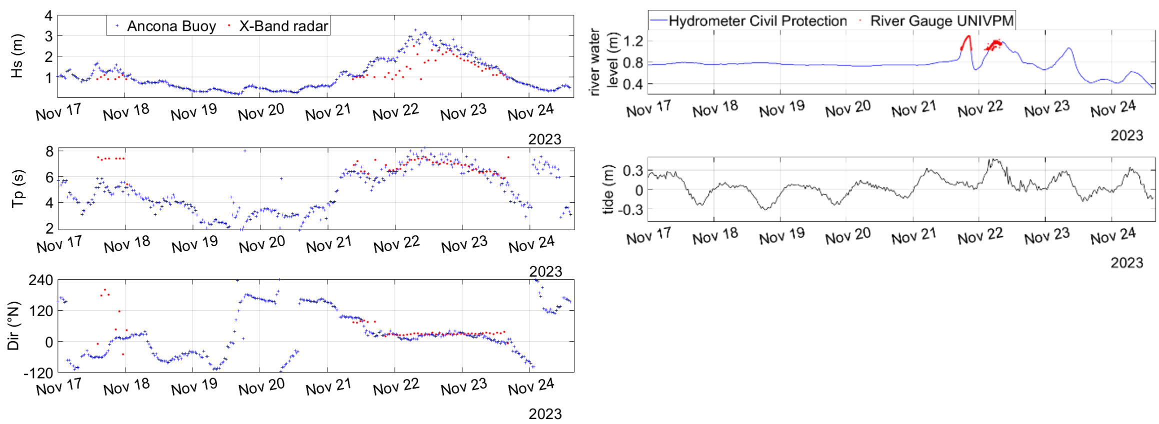

Figure 20. Left: sea forcing (Hs, Tp, Dir) during Test 1. Right: river water level and tide during Test 1.

Test 2

Objects were dropped from the water surface on November 24th around 250 m upstream of the river mouth. As clearly visible in Figure 21a, the water was extremely turbid and the diver's visibility was null. This condition occurred for every experiment in the river, but particularly on November 24th. During the first and second day of measurements, the diver held the GPM bounded to his hand, thus submerging it while going underwater. This probably caused a not perfect functioning, confirmed by a diver's measured route that not always corresponded to the real one. However, the object positioning was estimated combining measures, MultiBeam survey (Figure 21b), photo and video recordings. The survey was carried out on November 30th, when the heaviest UXOs were almost completely buried. However, some features attributable to the object can be recognized: the anchor is clearly visible in the center of the channel; a smooth pit in the riverbed is visible on the left of the anchor, probably due to the sinking of the 155mm cylinder; a small depression followed by an increase in the bed level downstream could indicate the 105mm projectile, head-down plunged in the mud. On the last day of the experiment, we tied the GPM to the diver's buoy, so that it remained always out of the water. This improved the quality of the track measured by the instrument.

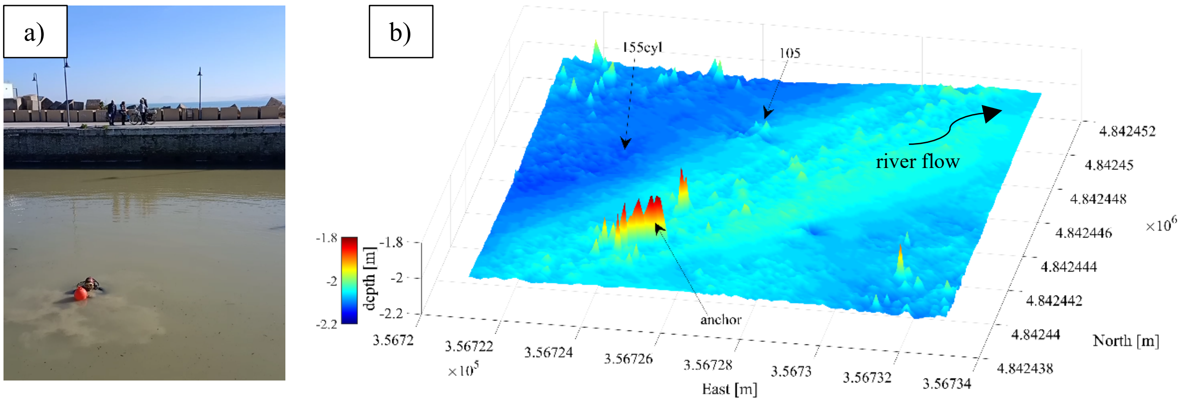

Figure 21. a) Measurements on November 24th (right bank of the river visible); b) 3D-view of the MultiBeam survey performed on November 30th.

Results of Test 2 are shown in Figure 22 and reported in Table 5. The 155mm cylinder and the 105 HE projectile were found head-down plunged in the mud layer, as occurred for the 155mm HE projectile in Test 1. It is very unlikely that they moved; indeed, they were found almost in the same position as where they were deployed. The small displacements reported in Table 5 are probably attributable to both inaccurate measurements and our estimate of the objects' position. A different behavior was observed for the 60mm mortar bomb, which did not bury, but migrated some meters downriver.

The mouth bar spanned again the whole cross-section of the river on November 24th, so that the sea storm occurred on November 25th-26th (Figure 23, right) could not penetrate into the river channel. On November 25th some moderate precipitation occurred, leading to an increase in the river water level, captured by both the Civil Protection hydrometer and the MORSE gauge (Figure 23, left). Due to the occlusion caused by the bar, the level slowly decreased the following days, until November 28th, when the level abruptly decreased in the wake of the start of some dredging operation. This probably triggered some river currents directed toward the sea that might have caused the migration of the 60mm mortar bomb. Another small storm occurred between December 2nd and 4th, from the SE, resulting in wave height recorded by the X-band radar smaller than 0.8m, thus not reported in Figure 23. Precipitation also occurred on the retrieval day.

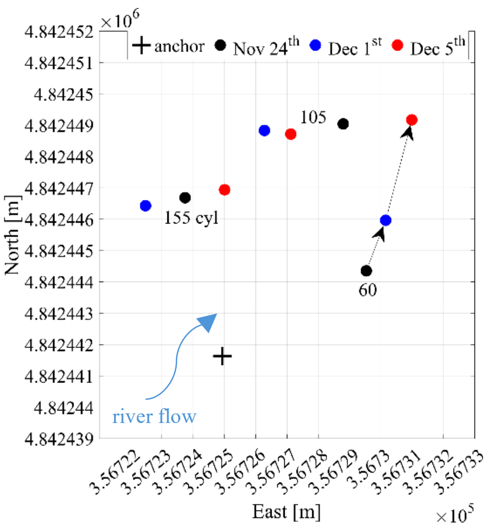

Figure 22. Object positions during Test 2.

Table 5. Object migration distances and burials in Test 2.

Object	December 1st		December 5th	
	M [m]	B [cm]	M [m]	B [cm]
155 cyl	1.3	50	2.6	50
105	2.5	40	0.8	60
60	1.7	-	3.3	-

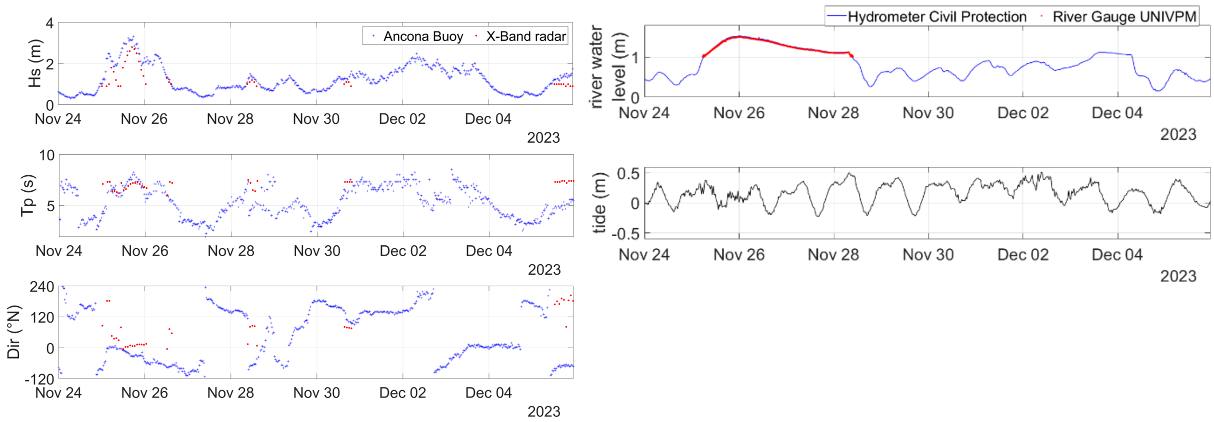

Figure 23. Left: sea forcing (Hs, Tp, Dir) during Test 2. Right: river water level and tide during Test 2.

Test 3

Four UXOs were dropped from the sea surface on December 20th around 300 m offshore from the river mouth (5m water depth), using two boats, one for the instrumentation and university personnel and the other as support for the diver activity. On December 20th and 27th and January 5th position measurements were performed both by the divers, using the GPM, and by SOCOTEC Italia S.r.L, using their instrumentation. The divers followed the same procedure used for the other tests. The measurements were repeated twice to improve their robustness. The GPM was always tied to the buoy, remaining outside of the water. Then, the diver searched again for the objects and reported to SOCOTEC where to measure. MultiBeam surveys, carried out by SOCOTEC in these days, are shown in Figure 24. The anchor is clearly visible in all surveys, while the 155mm HE projectile is visible in the second and third surveys. Correlation of the forcing conditions with the acquired measurements suggested to trust more the SOCOTEC data, showing no significant displacements from December 20th to January 5th. Indeed, no sea storms occurred during this period, the wave height always remaining smaller than 1 m (Figure 25). The erosion/deposition map between the surveys of January 5th and December 20th, shown in Figure 26a, highlights seabed erosion to the East and deposition to the West, suggesting some sediment transport in the E-W direction. Such sediment motion might have caused the small migration (less than 4m) of the objects toward the West.

On January 17th, after a NE wave event occurred on January 7th – 10th, the objects were found buried in the sand of approximately 50cm. SOCOTEC did not perform a survey after the storm, we can just assume that waves triggered a stronger fluidization of the seabed contributing to the burial of the objects.

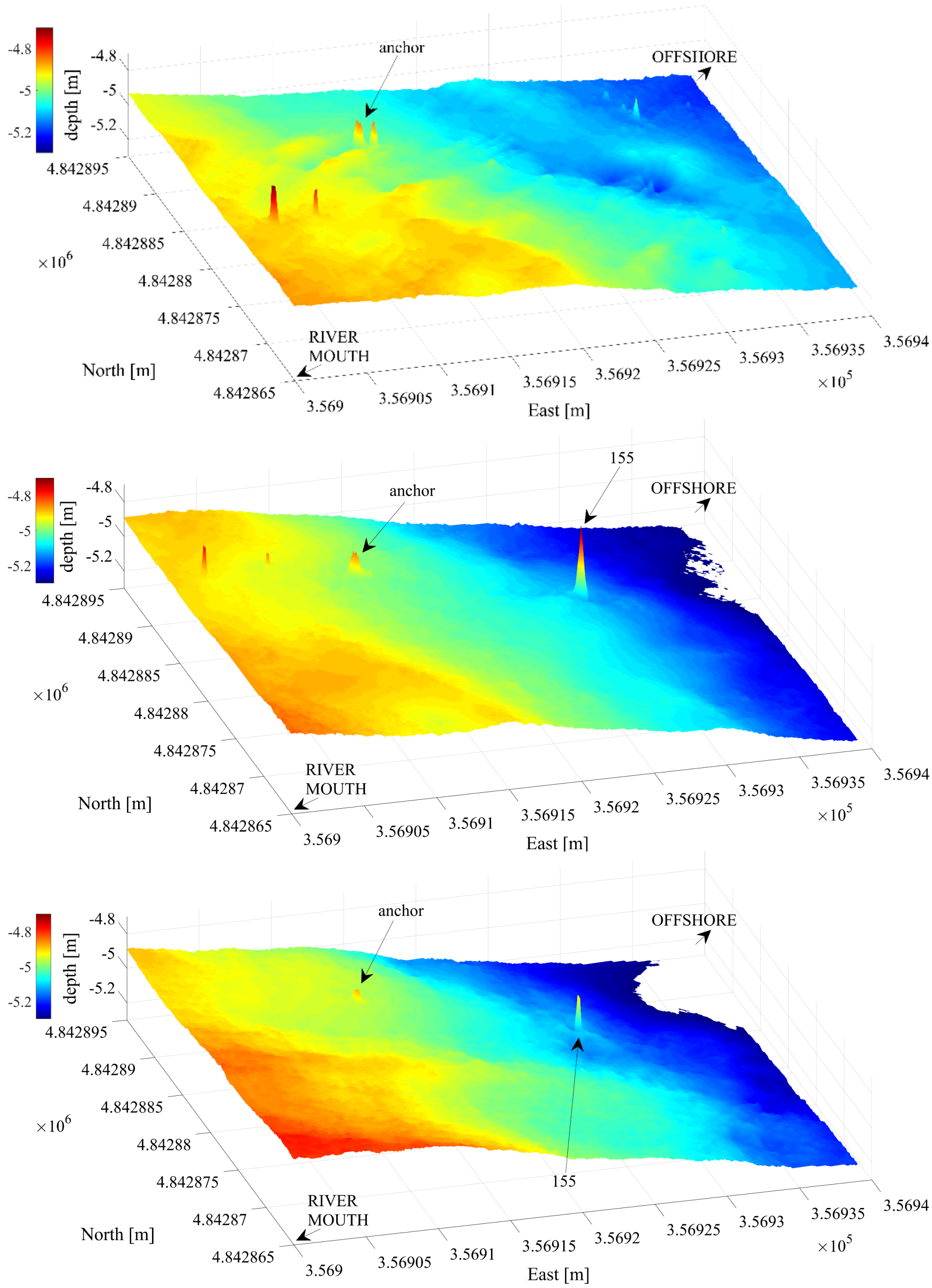

Figure 24. 3D-views of the surveys performed on December 20th and 27th and January 5th.

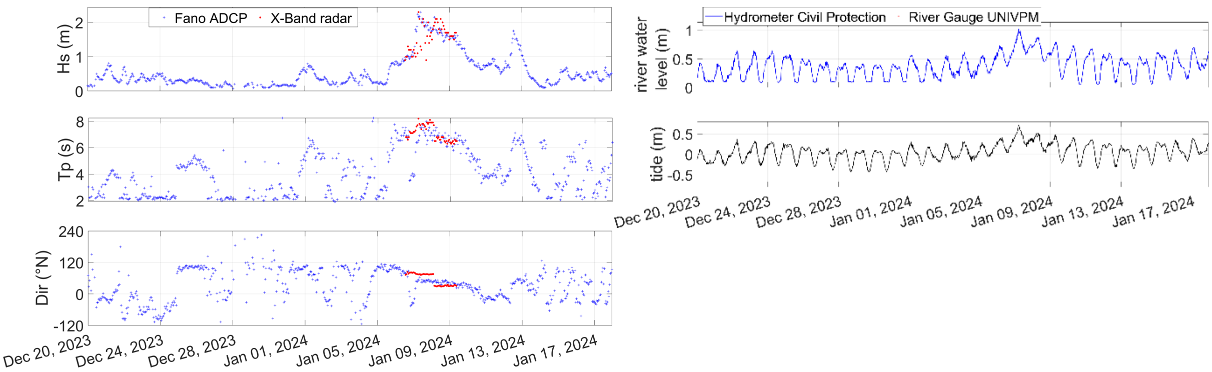

Figure 25. Left: sea forcing (Hs, Tp, Dir) during Test 3. Right: river water level and tide during Test 3.

Position measurements were performed only by the diver: the UXOs experienced some moderate displacements, as shown in Figure 27 and Table 6. Waves came from the East during the onset of the storm, then rotated towards NNE. The hydrodynamics of the area, where the UXOs were deployed, is influenced by the presence of the harbor. A Delft3D numerical simulation of Test 3, performed to obtain the inputs for UnMES, showed a dynamic evolution of the hydrodynamic field outside of the MR estuary, with the bed shear velocity rapidly changing direction. This could be the reason why the objects did not move all in the same direction. Moreover, based on the latest available survey (January 5^{th}), the displacements of the 105mm HE projectile and the 120mm mortar round were facilitated by the seabed slope: the UXOs probably rolled down from a higher to a more depressed area (Figure 26b).

Rennie et al. (2017 – MR-2227) proposed a critical threshold for the object mobility parameter θ_{cr} based on the ratio between the relative roughness of the seabed, k, and the object diameter D:

$$\theta_{cr} = 1.64 \frac{k}{D}^{0.71} = 1.64\, pb^{0.71}$$

Eq. 1

They found good performances if taking the effective roughness k to coincide with the burial depth at the time of motion inception, i.e. k=zb.
The object mobility parameter is defined as:

$$\theta_{obj} = \frac{U^2}{gD(S_0 - 1)}$$

Eq. 2

where U is the near-bed velocity, g is gravity acceleration and $S_0 = \rho_{obj}/\rho_w$ is the object relative density, with ρ_{obj} and ρ_w the object and water densities, respectively.

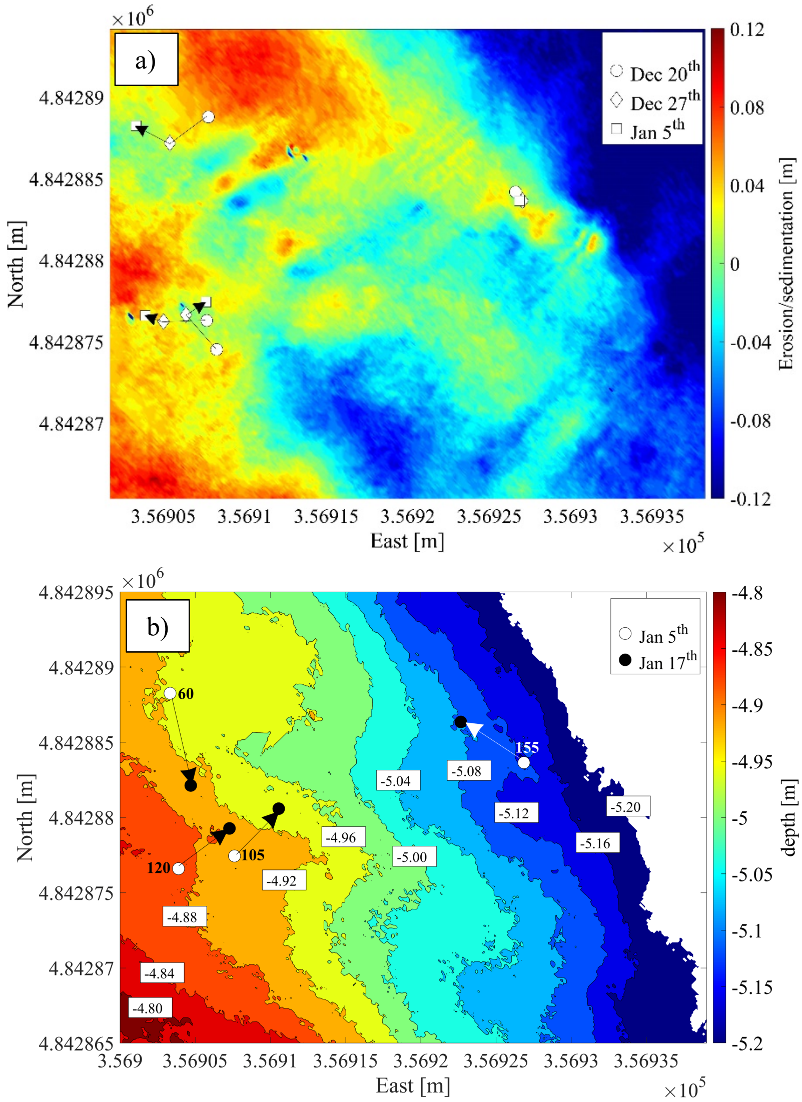

Figure 26. a) Seabed changes between December 20th and January 5th. Markers represent the UXO positions on December 20th (circles) and 27th (diamonds), and January 5th (squares). b) 2D contour plot of the survey carried out on January 5th, with UXO positions on January 5th (white circles) and 17th (black circles).

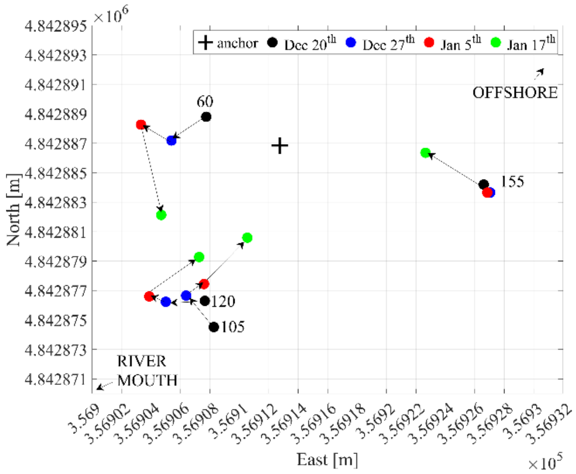

Figure 27. Object positions during Test 3.

Table 6. Object migration distances and burials in Test 3.

Object	Dec 27th		Jan 5th		Jan 17th	
	M [m]	B [cm]	M [m]	B [cm]	M [m]	B [cm]
155	0.7	-	0.2	-	5.0	65
105	1.3	-	1.4	-	4.3	60
120	3.7	-	1.2	-	4.3	62
60	2.9	-	2.3	-	6.3	56

We computed the near-bed velocity as the combination between a wave contribution, U_w, and a current contribution, U_b (Friedrichs, 2018 – MR-2224):

$$U = \sqrt{U_w^2 + U_b^2 + 2U_bU_w|\cos\beta|}$$

Eq. 3

being β the angle between U_w and U_b.

The bottom current velocity U_b was estimated from the depth-averaged current velocity U_c (MR-2733):

$$U_b = \frac{U_c\kappa}{\ln\left(^h/_D\right)}$$

Eq. 4

where κ is the Von Karman constant, 0.41, and h is the water depth.
U_c, U_w, and h were known from the Delft3D simulation of Test 3. The wave contribution to the near-bed velocity was much higher than the current contribution, as clearly visible in Figure 28a. Figure 28b shows the mobility parameter of the UXOs during Test 3. The horizontal dashed lines give the critical mobility parameter as a function of the initial burial depth. If the objects were almost proud (pb=1%), the storms occurred on January 7th – 10th and 12th would have mobilized them all. Increasing the initial burial depth up to 10% results in no mobility for the 155mm and 120mm UXOs. With even greater burial (pb=25%, pb=50%), only the 60mm mortar round would have exceeded the threshold for mobility. Since no significant events verified before January 5th, it is likely that the burial of the object was very small at the onset of the storm. This was also confirmed by the UnMES simulation of Test 3, showing a burial within 0% to 20% before the storm.

a) b)

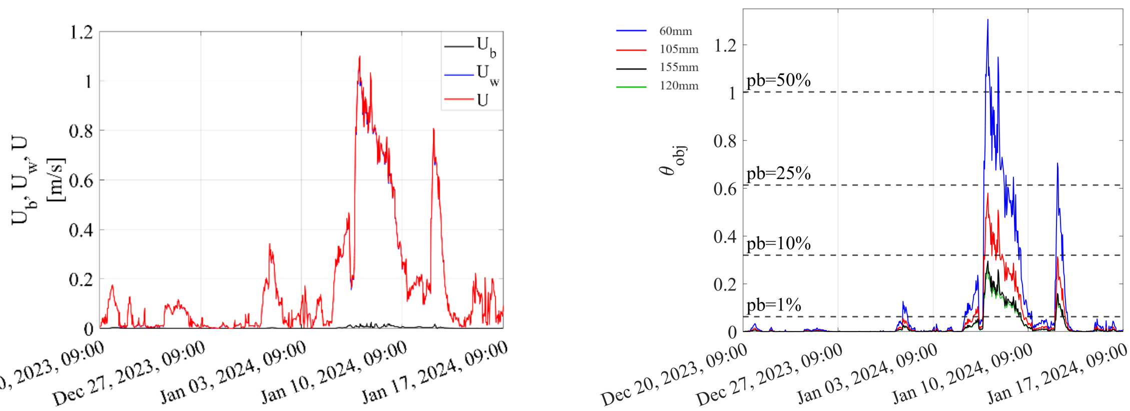

Figure 28. a) Bottom current velocity (for this plot, computed using D=60mm), near-bed wave orbital velocity and near-bed velocity during Test 3; b) mobility parameters for UXOs during Test 3 and critical mobility parameters as a function of the initial burial depth (dashed lines).

We also computed the UXOs burial depth using the equation for combined waves and currents given in MR-2227:

$$\frac{zb}{D} = 1.85\theta^{0.34}\exp\left(-2.5\cos\alpha - 0.6\right)\exp\left(-1.1\, U_{b||}/U\right)\left(0.1KC^{0.51}\right)$$

Eq. 5

Eq.5 expresses the dependence of the burial process on the sediment Shield parameter θ, the angle of attack of waves relative to the major axis of the object (α), the relative angle between waves and currents and the Keulegan-Carpenter number KC.
The sediment Shield parameter is computed as:

$$\theta = \frac{\frac{1}{2} f_w U_w^2}{g(\frac{\rho_{sed}}{\rho_w} - 1) D_{50}}$$

Eq. 6

being ρ_{sed} the sediment density and f_w the wave friction coefficient, computed according to Fredsoe & Deigaard (1992):

$$f_w = 0.04(\frac{a}{2.5 D_{50}})$$

Eq. 7

where $a = \frac{U_w Tp}{2\pi}$ is the amplitude of the near-bed orbital velocity.
In Eq. 5, $U_{b||} = U_b \cos\beta$ and $KC = \frac{UTp}{D}$. Since the angle of attack of waves relative to the UXOs major axes was not known, we assumed that $\alpha = 90°$. Since $\alpha > 53°$, the burial is the same as for $\alpha = 90°$ (Friedrichs et al., 2016). When the angle of attack becomes smaller, the scour under cylinders decreases (Cataño-Lopera & Garcia, 2007). At the same time, cylinders tend to rotate from an initial small angle to a larger angle, moving to a more stable position with the main axis perpendicular to the flow. Since the angle of attack was not known and given that UXOs tend to align perpendicularly to the flow, the dependence of zb/D on α was here neglected.
The computed values of z_b/D at the peak of the storm exceeded 1 for all UXOs, meaning that a complete burial was predicted, in agreement with our observations. However, the observed burial depth was even larger than that predicted by Eq.5. This is probably due to the fact that Eq. 5 is valid under low to moderate energy forcing ($\theta < 0.7$), while during the peak of the storm θ reached 1.18. Under high energy conditions, bed fluidization verifies, that is when water flows are strong enough to mobilize the entire seabed to some significant depth. In such conditions, UXOs sink if ρ_{obj} is larger than a critical value of the sediment density $\rho_{sed,cr}$=2.65 (e.g., Cataño-Lopera et al., 2007) and the burial depth increases. The experiment performed by Calantoni et al. (2019), in high energy conditions ($\theta \sim 1$), confirmed such statement. Moreover, in the field, a combination of multiple burial mechanisms can occur (bed fluidization, granular sorting, bedform migration) and lead to larger burial.

As observed by Traykovsky & Austin (2017 – MR-2319), also the time history of the forcing can determine which process between mobility and burial take place. An object migrates if it has no time to bury before the threshold for mobility is reached. This happens when the waves increase quickly. On the contrary, even low-density objects buries if the waves increase slowly. In Test 3, even if waves increased quite rapidly, S_0 was greater than 3 for all UXOs but the 60mm mortar round. Moreover $\rho_{obj}/\rho_{sed,cr} \sim \geq 1$ for all objects. Therefore, we observed the complete burial of all UXOs and just some moderate migrations, probably occurred before the peak of the storm was reached.

Figure 29 shows the UnMES results at the peak of the storm (January 7th, 10AM). At the location where the 155mm UXO was deployed (identified with a black square in the left panels), the model predicted, with a probability of 48%, burial depths of 50% to 75%. The burial we observed in the field was larger and exceeded 100% of the UXO diameter. On the other hand, the predicted migration distance and direction were in fairly good agreement with observations. Indeed, the most probable (98%) migration distance predicted by UnMES was in the range 0m to 5m in the NW direction, which agreed with the observed displacement of the 155mm projectile.

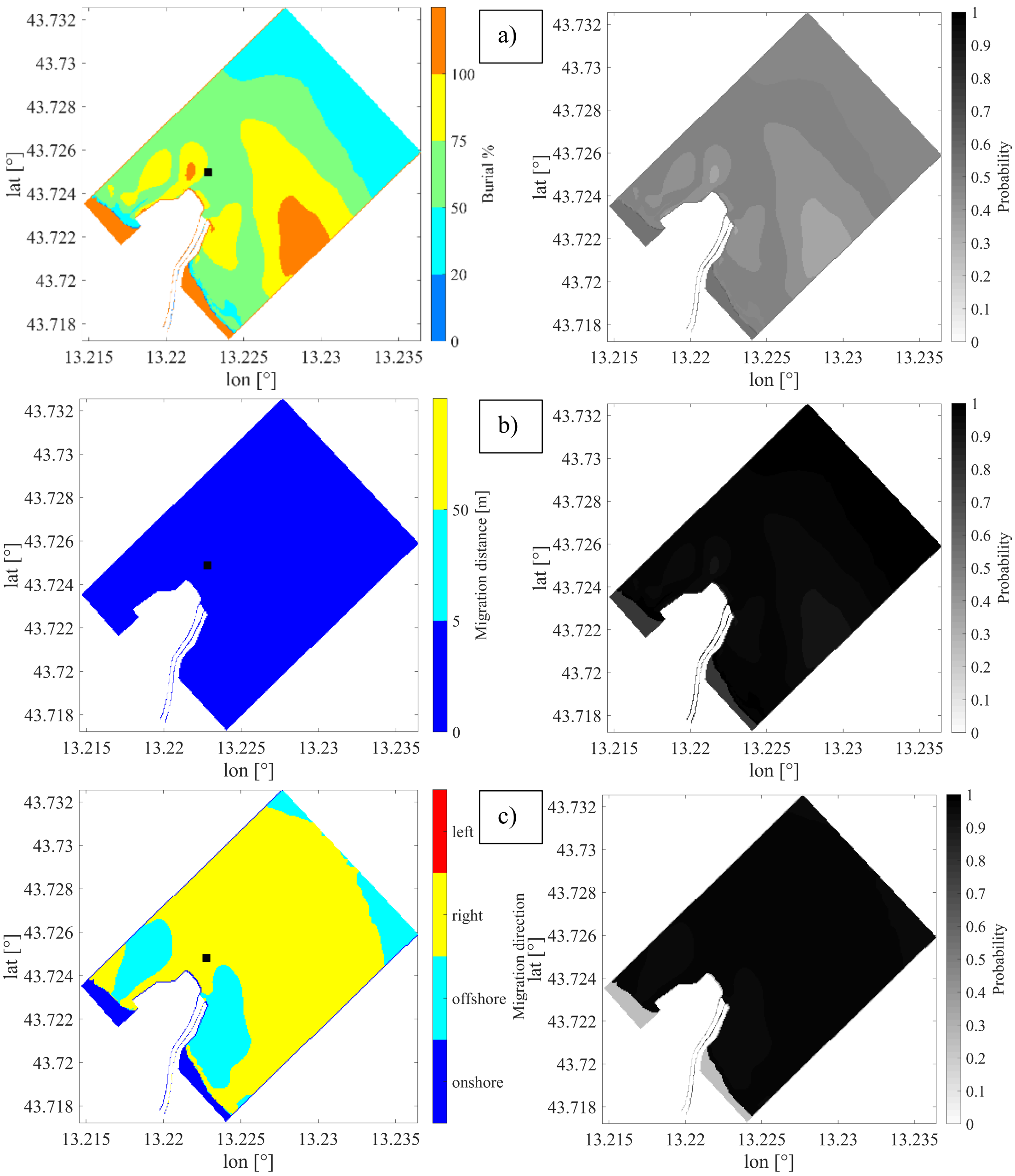

Figure 29. UnMES results for Test 3. On the left, most probable a) burial percentage relative to the object diameter; b) migration distance; c) migration direction. On the right, their respective probabilities of occurrence. Looking at the shoreline, left and right represent migration direction alongshore. The black squares indicate the location where the objects were deployed.

Test 4

The objects were dropped from the water surface on January 4th at the same location of Test 1, around 500 m upstream of the river mouth (Figure 30a). Both the divers and SOCOTEC acquired the position measurements twice; SOCOTEC also performed a MultiBeam survey just after deployment (Figure 30b). Differently from the other two tests in the river, the objects instantaneously buried in the mud after being dropped. This was the only time we observed some impact burial, which occurs when a mine is initially deployed and is a function of the velocity and attitude of the mine when it strikes the seafloor. Impact burial is common in areas with high porosity and muddy sediments (Wilkens & Richardson, 2007). However, since we always released the UXOs from the water surface and let them sink to the bottom, the objects' falling velocity was too small to cause impact burial in Tests 1 and 2. For Test 4, it is likely that the bearing strength of the mud layer was low enough to allow for instantaneous burial. Measurements from the diver, SOCOTEC and survey were in good agreement with each other.

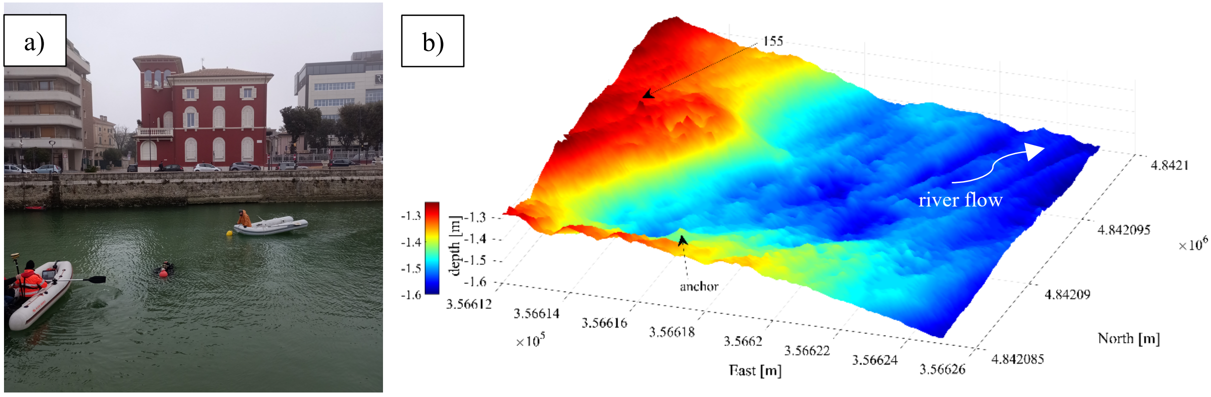

Figure 30. a) Measurements on January 4th (right bank of the river visible); b) 3D-view of the MultiBeam survey performed on January 4th.

Intermediate measurements were carried out on January 12th only by the diver, who struggled to stand still because of waves propagating upriver and an upstream-directed current. Measurements (Figure 31 and Table 7) showed a small upriver migration of the 155mm and 105mm HE projectiles, while a downstream displacement was observed for the 60mm mortar round. Since the diver was dragged upstream while measuring, the position data acquired on this day were considered not reliable. Furthermore, from videos and photos, only the 60mm UXO seems to have moved downstream. The burial depth increased for all the UXOs.

The objects were retrieved on February 2nd at low tide. While the heaviest UXOs were completely buried, the 60mm mortar round was found resurfaced on the riverbed. During Test 4, no river events occurred. Since at that time the sediment mouth bar was completely removed, the tide propagated upstream, as clearly shown by the comparison between the river water level and the tidal signal (Figure 32, right). Two wave storms occurred on January 7th – 9th and 20th – 22nd, both from the NE, thus directed perpendicularly to the river mouth. Waves easily entered the river and propagated upstream, as observed on January 12th. Both tide and river water level showed an increase in correspondence of the two storms. Indeed, here "tide" refers to the sum of the astronomical and meteorological components and, therefore, contains the storm surge that accompanies wave storms.

The displacements of the heaviest UXOs were really small (Table 7), suggesting that they got buried and experienced at most some small rolling/sliding toward minor depths. The migration from a higher to a more depressed area also occurred, more clearly, for the 60mm mortar bomb (Figure 33). Furthermore, the overall decreasing trend of the tidal signal, starting from January 20th, might have facilitated the downriver migration of the 60mm mortar round. In fact, as observed by several authors, the low tide speeds up the river flow towards the sea (Ruiz-Reina & López-Ruiz, 2021; Baldoni et al., 2021).

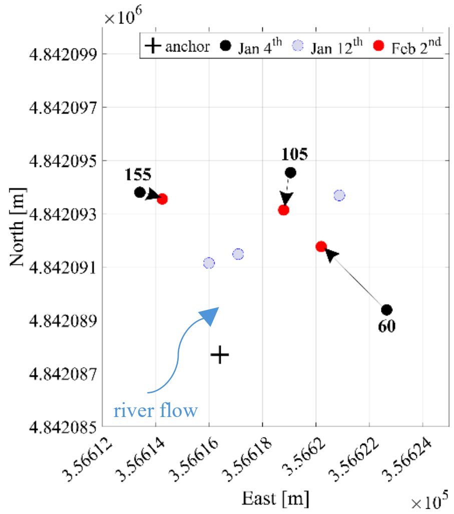

Figure 31. Object positions during Test 4.

Table 7. Object migration distances and burials in Test 4.

Object	January 12th		February 2nd	
	M [m]	B [cm]	M [m]	B [cm]
155	?	65	0.9	85
105	?	40	1.4	90
60	?	33	3.4	-

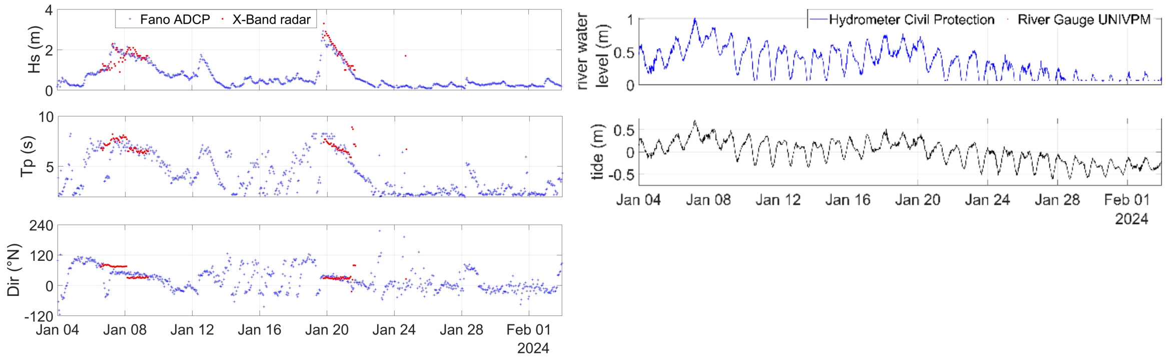

Figure 32. Left: sea forcing (Hs, Tp, Dir) during Test 4. Right: river water level and tide during Test 4.

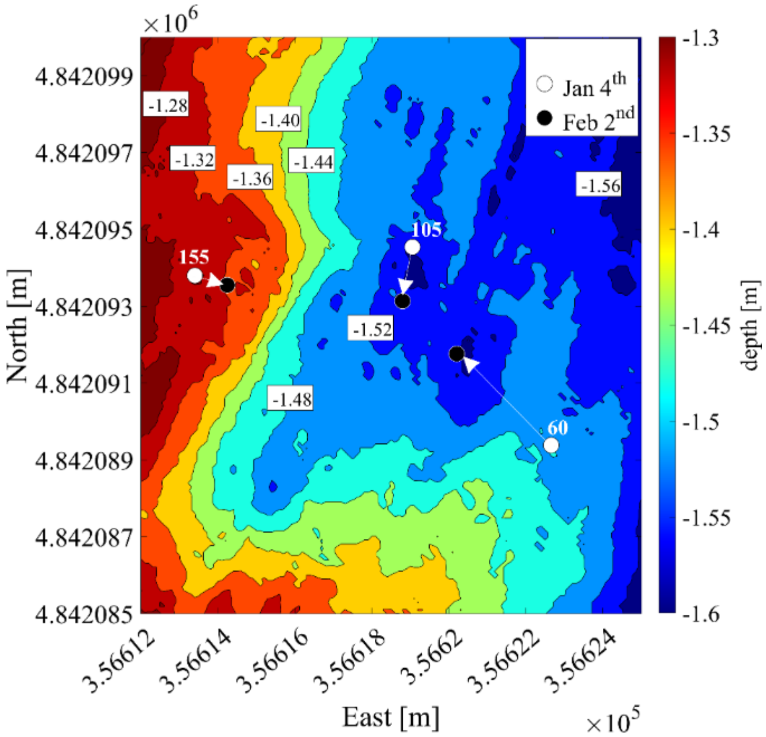

Figure 33. 2D contour plot of the bathymetric survey performed on January 4th. White and black circles represent, respectively, UXO positions at the deployment and retrieval time.

Test 5

Test 5 was performed at the river mouth, where the major interaction between the river and the sea is expected. Unfortunately, we could not observe the effect of such combination of forces on the UXOs behavior because calm conditions occurred during the experiment (Figure 34).

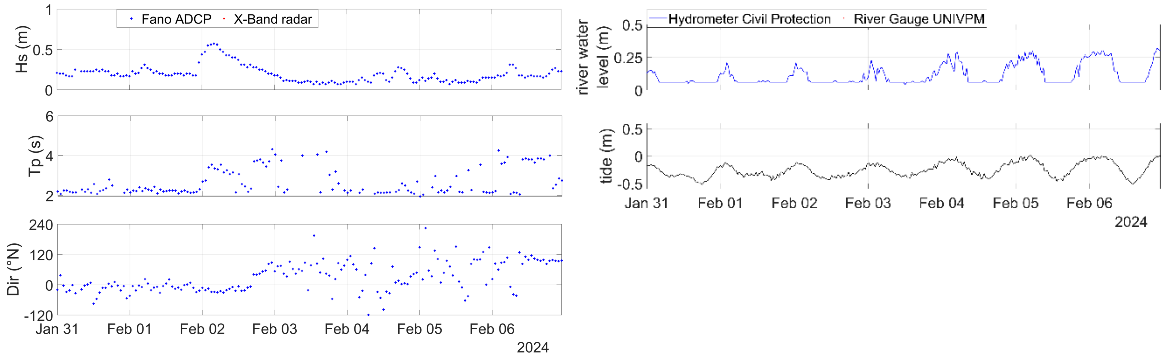

Figure 34. Left: sea forcing (Hs, Tp, Dir) during Test 5. Right: river water level and tide during Test 5.

The objects were deployed on January 31st. One 155mm HE projectile with an embedded GPM2 was deployed to continuously monitor its motion. Since no significant events occurred during this test, the underwater visibility was always optimal, allowing us to record a video using a GoPro fixed to the diver's mask. The video was acquired during the retrieval day, February 6th. Four video frames (one for each UXO) are shown in Figure 35, where an increasing amount of gravel is visible in correspondence of the 60mm mortar round, that was the ordnance located closest to the river mouth. Sand ripples and objects' scour pits are also visible form the images. The UXOs did not migrate during Test 5, since just very mild forces acted on them, and the burial is limited to few centimeters. The cut 155mm UXO had a reference system drawn on it and was deployed with this drawing on top and the head oriented toward NW. From the video frame of the retrieval time, it seems that it slightly rolled around its major axis since the drawn reference system was no longer on top.

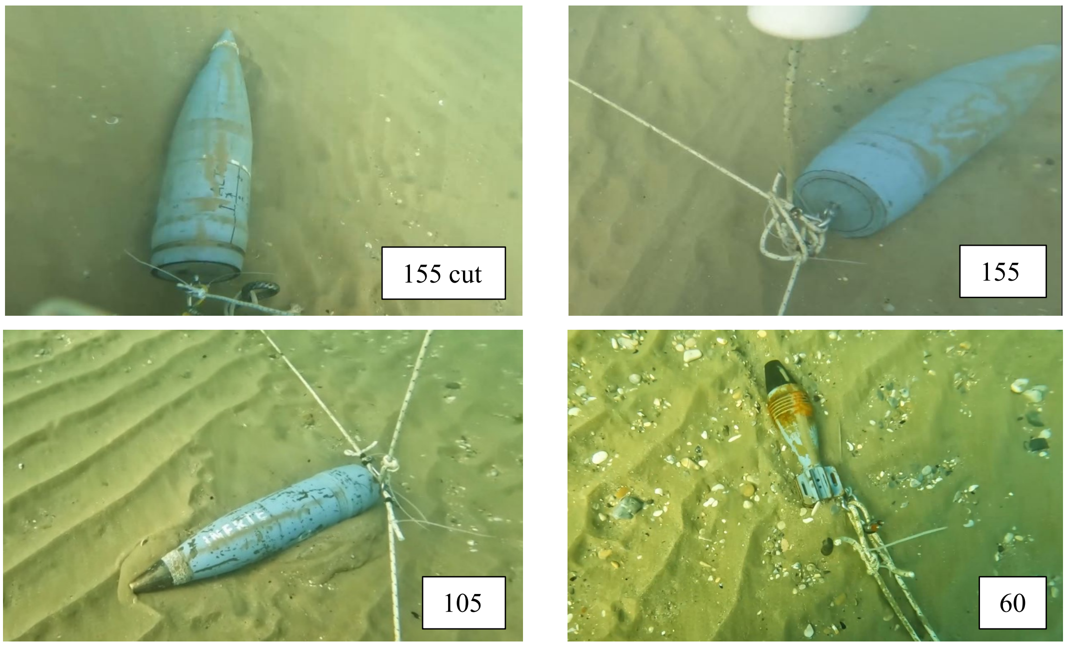

Figure 35. Underwater video frames showing the objects at the retrieval time (February 6th).

Plots of accelerations and Euler's angles recorded by the GPM2 inside the 155mm UXO are shown below and highlight the deployment and retrieval phases and a slight mobilization of the object on day 3 from the deployment. Black circles in Figure 36 indicate the deployment time, after which neither accelerations nor rotations of the object were observed, apart from one visible step in all the plotted timeseries. This was the time when, after deployment from the boat, the diver adjusted the orientation of the UXO, making the reference system facing up.

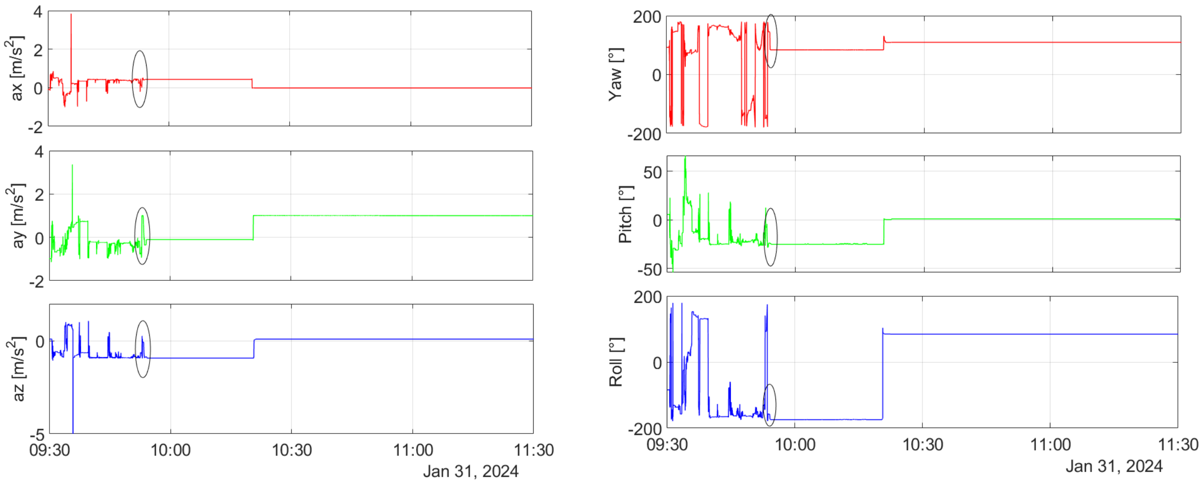

Figure 36. Accelerations and Euler's angles of the 155mm projectile at the deployment phase.

During the experiment, a slight variation in accelerations and Euler's angles was observed only once, in the evening of February 2nd (Figure 37). Waves were decreasing, after reaching a small peak at 4:00 (Hs=0.57 m), and rotating from N to ENE. The pitch started varying on February 2nd at 19:39, going from 0.98° to 4.64°; after one hour it went to −2.61°; finally, it increased again up to 0.59° and stabilized at 23:30. At the same time, the roll increased from 84.33° to 86.75°; then, it decreased again to 84.44°; finally, it stabilized at 86.59°. The yaw showed smaller variations (±1°). This almost null mobility was expected, since no significant forcing occurred during the test. However, the GPM2 showed good performances in capturing also the smallest variations of the accelerations and Euler's angles. The 2° rotation around the x-axis of the ordnance confirms what we observed from the video, which is a small rolling of the UXO, perhaps indicating an adjustment over sand ripples.

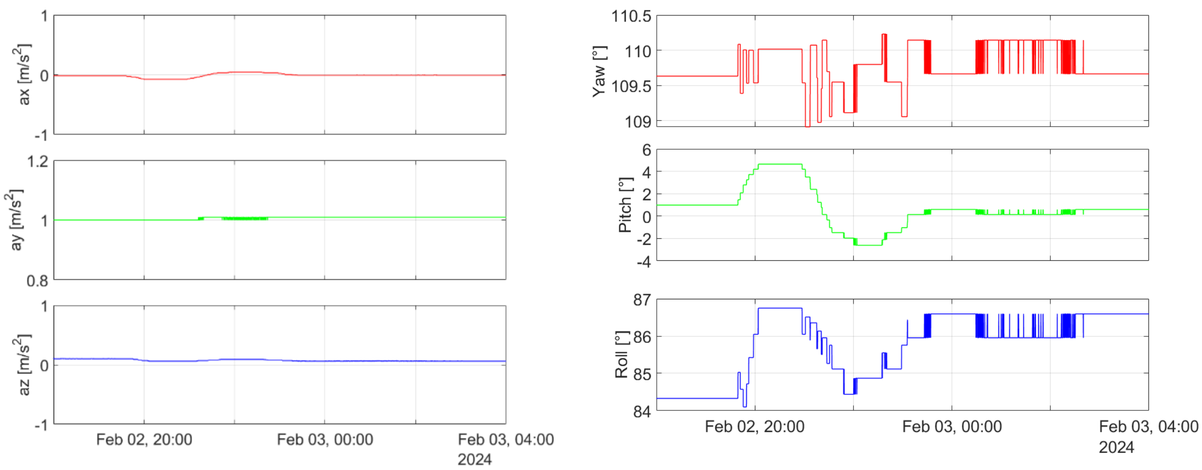

Figure 37. Accelerations and Euler's angles of the 155mm projectile on February 2nd.

The retrieval phase is also clearly visible from the GMP2 data and is highlighted by black circles in Figure 38.

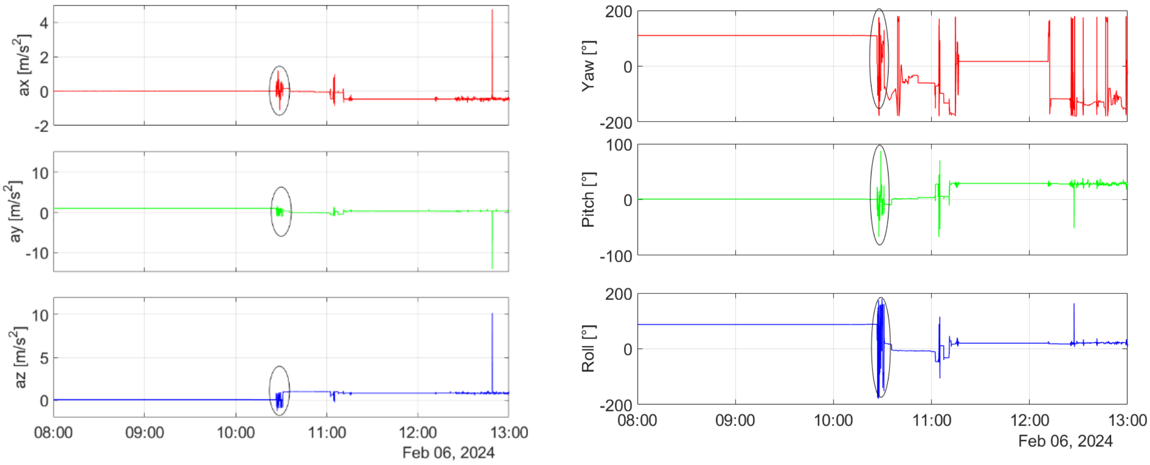

Figure 38. Accelerations and Euler's angles of the 155mm projectile at the retrieval phase.

Conclusions and Implications for Future Research

This study represents a first attempt to study mobility and burial of UXOs in a complex environment characterized by the simultaneous actions of river and sea forcing and by the presence of heterogeneous sediment. The instrumentation already existing at the mouth of the MR provided useful data to: i) characterize the hydrodynamic of the site and ii) run some preliminary Delft3D morphodynamic simulations, based on an already validated model setup. Knowledge of the hydro-morphodynamic of the estuarine area allowed us to better plan the experimental campaign. During the project, MultiBeam surveys were performed to reconstruct the bathymetry of the study area, before and after an important dredging operation. In addition, surveys were also carried out to retrieve the position of the UXOs. However, we found that only the anchor and the 155mm projectile could be recognized from the MultiBeam surveys. The GPM used to measure the UXO position showed good results when fixed on top of a surface buoy carried by the diver. The major error in the positioning was attributable to the diver's ability to stand at the vertical of the objects and increased with the water depth. The error reduced using the instrumentation by SOCOTEC, in which the GPS was located on top of an extendable rigid rod. This aspect needs to be addressed in future works. The internal instrumentation of a 155mm projectile showed good performances, recording accelerations and rotations of the object continuously for 7 days. In the future, with a proper calibration of the instrument, this technique will provide a 3D representation of the object motion. Finally, the pinger-receiver system was useful to find the objects when the underwater visibility was too low. Since the pingers stop working if they got buried, we tied them to the UXOs with a 1m rope and small floaters, to prevent their burial.

To observe the role of several forcing combinations and soil types, we performed a total of five field tests at different locations of the estuarine area: 1) in the river, where the bed is mainly characterized by cohesive materials and a thick layer of mud (around 60cm); 2) at the river mouth, where the river/sea interaction is strong and the sediments are mainly sand and gravel; 3) in the sea, where the bed is completely sandy. Although the field tests were planned to be performed in the most energetic season of the year, just few moderate events occurred. In particular, it was not possible to observe the effect of river discharges since only light precipitations occurred. Tests performed along the river showed the complete burial of all the UXOs in the muddy layer, with re-exposure of the 60mm mortar rounds, which also experienced the largest migrations (<5m). A small amount of the burial could be attributable to impact burial, since objects were dropped from the water surface, but the main cause for burial was most likely the exceeding of the sediment bearing capacity. This mechanism was already observed in the literature (e.g., Richardson et al., 2001; Inman & Jenkins, 2002; Shain et al., 2012; MR-2730), also associated with migration since, during storms, both the mine and muddy bed may move as a unit. The role of sediment type and sorting also seemed to play a role in the UXO behavior, since the 60mm mortar bomb resurfaced in correspondence of a gravel spot. In the test performed at sea, UXOs remained almost proud on the seabed, until a wave storm triggered bed fluidization, causing the complete burial of the objects. The equation for the burial depth found in MR-2227 correctly predicts the complete burial of the objects, even if the observed burial depth was larger than the predicted one. In high energy conditions, i.e. during storms, several studies (Cataño-Lopera et al., 2007; Calantoni et al., 2019) observed the increase of the burial depth with respect to that computed with the MR-2227 equation, valid for low to moderate forcing. The UnMES simulation of Test 3 was run for a 155mm projectile and underestimated the burial depth, giving 50% to 75% burial at the peak of the storm. Based on the critical threshold for motion defined by Rennie et al. (2017), the storm would have caused the mobilization of all the UXOs if their initial burial was less than 7%. Since no significant events occurred before the storm, we can assume that the burial was small. The UnMES simulation of Test 3 also confirmed that the most probable burial before the storm was in the lowest range (0% to 20%). Our observations showed some displacements after the storm, as expected, and were in agreement with the predicted migration distances (0m to 5m) and direction (to the NW) for the 155mm UXO. Some very small migration was observed also before the storm. This could be attributable to the rolling of the objects from a higher to a more depressed area, but also to non-accurate measurements, since the object mobility parameter should not have exceeded the threshold for initiation of motion, apart from the 60mm UXO.

Results of the project provided information on UXOs mobility and burial in an estuarine environment characterized by multiple forcing actions and mixed sediments, this making it very interesting and complex. Field observations were interpreted on the basis of existing literature, showing a quite good match. Furthermore, UnMES predictions of probable migration agreed with observations, while those for burial underestimated the observed burial depth. Overall, this work proposed an approach that combines field observations and modeling to study and predict UXO mobility and burial in a complex and dynamic environment, providing interesting results and hints for future research.

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Appendices

Appendix A. Characteristics of GPM sensors

GeoPoseModule: An "intelligent" pose-tracking platform to support object deployment and recovery underwater.

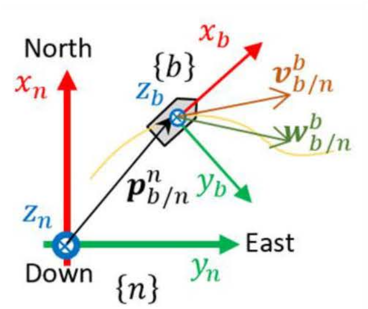
Introduction

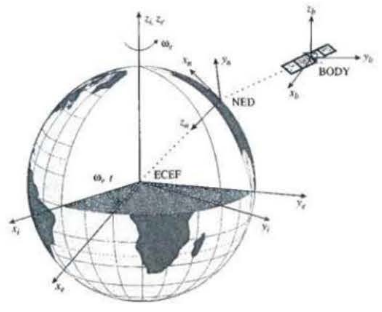
GeoPoseModule (GPM) is an "intelligent" pose-tracking platform supporting underwater object deployment and recovery. GPM has been developed in two formats and for different experimenting phases: GPM1 is for logging the position of objects at a determined time by surface, and GPM2 is for tracking an object from the deployment time in the end (at minimum 3 days of immersion).

The main differences between GPM1 and GPM2 are the battery capacities and the IMU accuracy.

GPMx implements a geolocation system for experimental setup made of small objects submerged for not a long time (less than 7 days) in a structured environment, not more deep than 5m and with the possibility of periodic diver surveys.

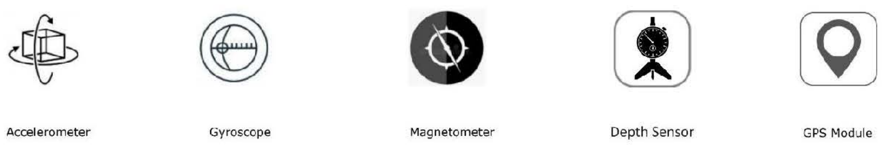
This can be achieved by integrating an Inertial Measurement Unit (IMU) and implementing the Mahony Orientation Filter to enhance vehicle orientation. In parallel, a data fusion system (based on an extended Kalman filter and a generic Fossen dynamic model of a submerged object) will be developed to combine GPS and IMU data for accurate three-dimensional position estimation.





The GPMx is an IMU/AHRS-based sensor device that detects acceleration, angular velocity, angle, magnetic field, pressure, and GPS data. The robust housing and the small outline make it perfectly suitable for marine applications such as condition monitoring and predictive navigation. Configuring the device enables addressing various applications by interpreting the sensor data by smart algorithms and Kalman filtering.

BUILT-IN SENSORS



Base model and calibration.

GeoPoseModule (GPM1): Diver's use. Developed and verified at the swimming pool and in a real environment (river) compared to Garmin GPS73 surface GPS logs.

Future implementation (at request): WiFi/Bluetooth/Lora/4G real-time connection.

GeoPoseModule (GPM2): Object's use. Calibration of the device in relation to the object's magnetic distortions.

Future implementation (at request): WiFi/Bluetooth/Lora/4G real-time connection.

GeoPoseModule (GPM1): Diver's use

GeoPoseModule (GPM2): Object's use

Measurement Range & Accuracy		
Sensor	**Measurement Range**	**Accuracy / Remark**
Accelerometer	X, Y, Z, 3-axis ±16g	Accuracy: 0.01g Resolution: 16bit Stability: 0.005g
Gyroscope	X, Y, Z, 3-axis -±2000°/s	Resolution: 16bit Stability: 0.05°/s
Magnetometer	X, Y, Z, 3-axis ±4900μT	0.15μT/LSB typ. (16-bit) AK8963 Magnetometer Chip
Angle/ Inclinometer	X, Y, Z, 3-axis X, Z-axis: ±180° Y ±90° (Y-axis 90° is singular point)	Accuracy:X, Y-axis: 0.05° Z-axis: 1° (after magnetic calibration)
Depth meter	1-axis	TbD
GPS Module	Altitude :50000m Speed Velocity:50000m/s	Position Accuracy: 2.5m (TbD) Direction Accuracy :0.5°

Accelerometer Parameters

Parameter	Condition	Typical Value
Range		±16 g
Resolution	±16g	0.01(g/LSB)
RMS noise	Bandwidth =100Hz	0.75~1mg-rms
Static zero drift	Placed horizontally	±20~40mg
Temperature drift	-40° C ~ +85° C	±0.15mg/℃
Bandwidth		5~256Hz

Gyroscope parameters

Parameter	Condition	Typical Value
Range		±2000° /s
Resolution	±2000° /s	0.05(° /s)/(LSB)
RMS noise	Bandwidth =100Hz	0.028~0.07(° /s)-rms
Static zero drift	Placed horizontally	±0.5~1° /s
Temperature drift	-40° C ~ +85° C	±0.005~0.015 (° /s)/℃
Bandwidth		5~256Hz

Magnetometer parameters

Parameter	Condition	Typical Value
Range		±2Gauss
Resolution	±2Gauss	0.0667mGauss/LSB

Pitch and roll angle parameters

Parameter	Condition	Typical Value
Range		X:±180°
		Y:±90°
Inclination accuracy		0.2°
Resolution	Placed horizontally	0.0055°
Temperature drift	-40° C ~ +85° C	±0.5~1°

Heading angle parameter

Parameter	Condition	Typical Value
Range		Z:±180°
Heading accuracy	9-axis algorithm, magnetic field calibration, dynamic/static	1° (without interference from magnetic field)
	6-axis algorithm, static	0.5° (Dynamic integral cumulative error exists)
Resolution	Placed horizontally	0.0055°

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GPS parameter

Index	Parameter
Signal Reception	BDS/GPS/QZSS/GLONASS
Cold Start TTFF	⩽32s
Hot Start TTFF	⩽1s
Recapture TTFF	⩽1s
Cold Start Capture Sensitivity	-148dBm
Hot Start Capture Sensitivity	-156dBm
Recapture Sensitivity	-160dBm
Tracking Sensitivity	-162dBm
Positioning Precision	<2.5m（CEP50）
Speed Measurement Accuracy	<0.1m/s（1σ）
Positioning Update Rate	2Hz
Protocol	NMEA0183