Using combined geotechnical and geophysical methods for site characterization of ultra-shallow submerged sites

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ABSTRACT

Ultra-shallow underwater environments (average water depth ≲ 1 meters) in rivers, estuaries, and coastal zones represent the transition between water bodies and landmasses relevant for many engineering applications including utilities and transportation, habitat monitoring and restoration, and resilience to extreme flood and coastal storm events. With climatic shifts and an increased occurrence of extreme events, ultra-shallow underwater environments and inundation zones receive increasing attention. However, the increasing need for data revealed current limitations in safe accessibility and survey methodologies suitable for those conditions. Adaptation of geotechnical testing methods such as cone penetrometer testing and free fall penetrometer testing enable updated geotechnical testing capabilities, but these methods still require physical access to the measuring site which may be compromised by significant flow conditions, unknown debris and bottom conditions, limitations in access points and time, and combinations thereof. Remote sensing using optic sensors from unmanned aerial vehicles as well as from satellites offer strategies of soil classification in a rapid manner and without need for physical access if water conditions are clear. Advances in geoacoustic surveying, particularly regarding the use of sonars in ultra-shallow environments offers seabed surveying even in murky waters. Fusing geoacoustic and/or optic data with geotechnical point measurements enables the optimization of data collection in ultra-shallow underwater environments or inundation zones in a safe and efficient manner, contributing also to available data from these environments to advance our understanding of soil mechanics in inundation zones and ultra-shallow waters. Here, an overview of available methods and recent advances in methodologies is presented supported by case studies including riverine and coastal environments.

Keywords: ultra-shallow underwater environments, site characterization, geotechnical, geophysical

1. Introduction

Ultra-shallow underwater environments (mean water depth ≲ 1m) connect water bodies and landmasses. Thus, subaquatic as well as water-fringing engineering applications often include ultra-shallow underwater environments. Nevertheless, these environments have often represented a gap in field data collections resulting from methods being typically developed for subaquatic or terrestrial application. Novel developments in remote sensing, geotechnical field testing, as well as geophysical surveying offer new opportunities to fill these gaps. Fusion of such data products can increase efficiency in data collection and can expand data volumes.

Satellite-based and aerial remote sensing techniques have traditionally been applied to map land-use as well as geomorphological changes (e.g., Fabbri et al. 2020; Misra and Ramakrishnan 2020). Recently, the improvement of remote sensing products and of remotely sensed data analysis tools has also enabled the derivation of soil properties (such as composition, type, moisture content, friction angles, and others) from remotely sensed data (e.g., Mulder et al. 2011; Stark et al. 2017; Park 2019; Paprocki et al. 2022). In the case of moderate flow conditions and low turbidity, optic remote sensing can even be utilized to view through the water columns, particularly in ultra-shallow environments (e.g., Partama et al. 2018).

Portable geotechnical in-situ field testing equipment that can be deployed and carried by a person wading or from small vessels enables geotechnical data collection in ultra-shallow water depths without the need for amphibious test rigs or cranes that stretch from land over a water body. While those rigs are more commonly available, they are typically slower and costly, often limiting the data volume. Portable free fall penetrometers (PFFP) or dynamic cone penetrometers can offer insights into geotechnical properties of the upper meter to meters of the river- or seabed in an efficient manner (e.g., Stark et al. 2014; Jaber et al. 2021).

Geophysical surveying using sonar technologies is a common tool in offshore site investigations. However, they have rarely been considered in ultra-shallow environments due to impacts on data quality from the close distance between seabed and water surface. Over the last decade, sonar developers have expanded their technologies further towards use in ultra-shallow environments. Particularly, dual-frequency single beam echo sounders have shown to be able to measure bathymetry confidently towards water depths as shallow as 30 cm while additionally providing some information of seabed composition through a lower frequency channel with some seabed penetration (e.g., Bio et al. 2020). Side scan sonar systems can nowadays scan a width of about ten times the distance to the seabed, meaning that a sensor distance to seabed of only one meter would still enable to scan the seabed in a 10 m distance, and thus, prove well suited for shallow water environments (e.g., Borelli et al. 2022).

In this article, the benefits of geophysical and geotechnical data fusion are initially discussed using an example data set collected during the phase 2 reconnaissance mission in response to the Western European floods 2021 by the Geotechnical Extreme Events Reconnaissance (GEER) association (geerassociation.org) (Gardner et al. 2023a).

2. Methods

2.1. Regional context

The data example is the pink pedestrian bridge in Mayschoss, Germany (N50º31'53.19"; E7º1'35.47"). The bridge failed during the severe western European flood event in July 2021 (Fig.1)

Figure 1. Pink pedestrian bridge in Mayschoss, Germany after the July 2021 western European flood event.

The bridge crossed the Ahr river approximately 100m downstream of a <90º right bend of the river and just in front of an approximately 90º left bend of the river (Fig. 2). The riverbank is fringed by an asphalted road on the northern bank and by steep rock walls and a shoal in the right bend on the southern riverbank. The terrain is overall steep with little flood plains. The riverbed in this section is mostly composed of gravel and cobbles, and the mean water depth is well under 1m.

At the time of the survey, the bridge was severely damaged but still in place as shown in Fig. 1. One of the bridge abutments was washed away by the flood, while the other one was damaged but still standing and the bridge deck was hanging into the river. The damaged bridge was removed about 9 months after the flood event, but it was still in place in the state shown in Fig. 1 during the measurements. Other than stabilization of the fringing street, no alterations had been made to the area between the flood and the measurements. High-water marks suggested that flood waters reached well above the bridge deck (Gardner et al. 2023). Measurements during the GEER phase 1 data collection efforts in August 2021 shortly after the flood were limited to ground-based and aerial photographs. Measurements during the GEER phase 2 data collections efforts in March 2022 included aerial imagery including multispectral imagery, lidar scanning, bathymetric surveying, side scan sonar scanning, chirp sonar scanning, portable free fall penetrometer measurements, and sediment sample collection. Here, we focus on the in-water measurements. They were challenged by a lack of a boat ramp, water depths ranging from 0.3 m to 3 m (the latter was unknown prior to the survey), and obvious debris including a large structure at the surveying location (i.e., a partial bridge with questionable stability). It was also unknown at that time how much debris was in the water.

Figure 2. Google Earth image from March 2020 (prior to flood) showing bridge and river bends.

2.2. Geoacoustic surveying

A dual-frequency single-beam sonar deployed from a *Teledyne Marine Z-boat 1800* (Fig. 3) was used to measure bathymetry. The Z-boat was remotely operated by staff of the RAPID-NHERI reconnaissance facility, University of Washington. Bathymetric mapping was performed using the commercial software package *Hypack* also by RAPID-NHERI staff members. The Z-boat was able to operate at water depths > 0.3 m and deeper and was remotely controlled but accompanied by a support person nearby and with the ability to access the water due to the possible hazard of debris under the water surface.

A *Kongsberg Mesotech MS-1000* rotary side scan sonar was deployed to image the riverbed to investigate the presence of debris as well as the contact of the hanging bridge deck with the riverbed. While the rotary side scan sonar is typically deployed using a tripod that is placed on the seabed. The risk of unknown bathymetry and debris led to the decision to deploy the side scan sonar from an inflatable vessel kept stationary through guidance of a rope that was installed from one riverbank to the other or by landing the vessel at the riverbank (Fig. 4). Side scan sonar is creating an image of the riverbed from acoustic backscatter of a transmitted and received high-frequency acoustic signal. It is a common tool to image seabeds and riverbeds, particularly around infrastructure systems but is just recently considered for ultra-shallow environments (Borelli et al. 2020).

A *SyQwest Stratabox* chirp sonar pinging at a frequency sweep of 8-12 kHz was used to attempt to resolve riverbed stratigraphy. The device has a minimum operational water depth of approximately 1m, limiting the possible measurement locations in this location.

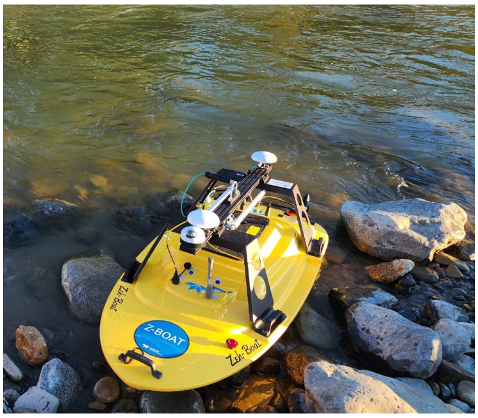

Figure 3. Photo of the Z-boat.

Figure 4. Side scan sonar arrangement. The sonar is hanging off the stern of the inflatable vessel.

2.3. Portable free fall penetrometer and sediment samples

Portable free fall penetrometer (PFFP) measurements using the *BlueDrop* were conducted from an inflatable vessel (Fig. 5) in all locations that did not feature an obvious cobbly riverbed or debris based on the side scan sonar image and visual inspection. The probe was deployed and retrieved by hand. The deployment strategy followed conceptually work by Jaber et al. (2021). The PFFP measures deceleration and ambient pressure behind the nose cone, allowing to derive information about sediment type, layering, and geotechnical engineering properties over the penetration depth. The penetration depth is limited to typically around 0.1-0.2m in coarse-grained sediments and < 1m in fine-grained sediments. The rugged design allows for unplanned impacts with cobbles, but such data are not informative beyond the information that the probe impacted with a rock.

Sediment samples were collected of gravelly to fine-grained sediments by inserting a push tube by hand and recovering the sample. The samples were collected mostly for grain size analysis.

Figure 5. Portable free fall penetrometer measurements.

3. Results

3.1. Geoacoustic surveying

Bathymetric surveying by the Z-boat was not conducted along a fixed grid but by zigzagging across the river (Fig. 6 hot-cold color bathymetry map) from well upstream of the bridge to well downstream of the bridge. The goal was to obtain as dense of a spatial coverage as possible while also avoiding debris and promoting safety for gear and personnel. This approach led to a good coverage enabling to draw clear conclusions on the bathymetry in this river section. The data shows an overall ultra-shallow (<1m) river section with limited to no channel morphology upstream of the bridge bend, a clearly present central channel with about 2m water depth just downstream of the bridge bend, and a decreasing channel feature with increasing distance downstream from the bridge bend (Fig. 6). Significant channel deepening (~ 3m) within the bend representing a major scour hole (> 3m) near the contact location of the bridge debris with the riverbed. It can be suspected that the significant channel deepening in the bend is at least partially if not mostly driven by the presence of the bridge debris. The deep channel in the bend leads to a major riverbed slope on the inner meander side from the deep spot (> 3m) to the inner meander shoal of fine sediment deposits (~ 0.1m) over a distance of < 10m.

The bathymetry is displayed with the local topography displayed as a digital terrain model (DTM) derived from unmanned aerial vehicle imagery (Fig. 6 purple color topography map). The DTM shows how the river is wedged between two steep hills which funnelled flow along the river course in this area. The narrow valley topography with hills being composed of hardly erodible rock was a major factor in the severe infrastructure damages and destruction of bridges in the area. Fig. 7 displays the bathymetry and topography on the same scale, providing a more holistic and seamless picture of topography to bathymetry.

The side scan sonar images displayed a highly variable riverbed featuring fine-grained sediments, gravel, cobbles, and even substantial boulders (Fig. 8 left). They also showed contact of bridge beams and cables with the riverbed. The use of the rotary side scan sonar from a vessel and without of the use of its seabed tripod was found generally possible but unfavourable

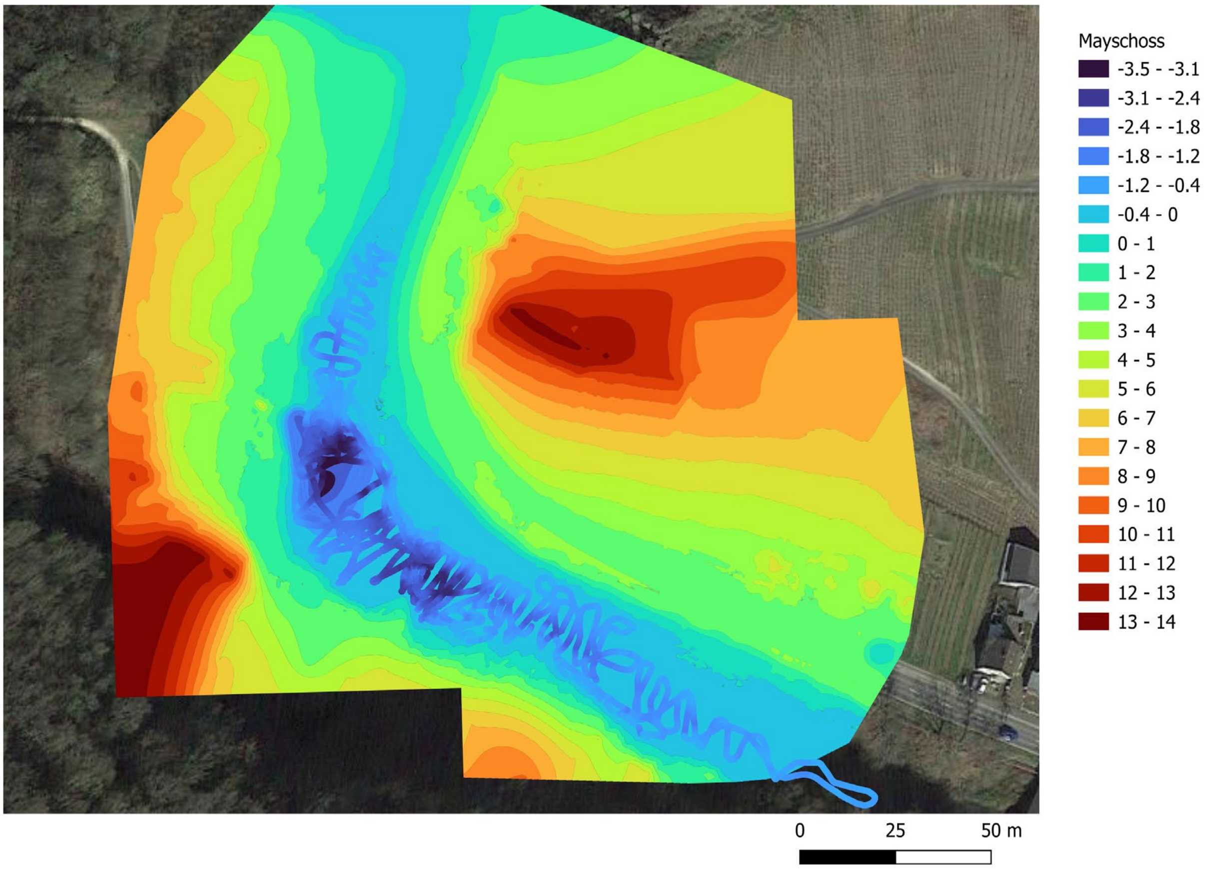

Figure 7. Full terrain to bathymetry model showing elevation as color map in meters and with 0 m indicating the water surface at the time of the measurements.

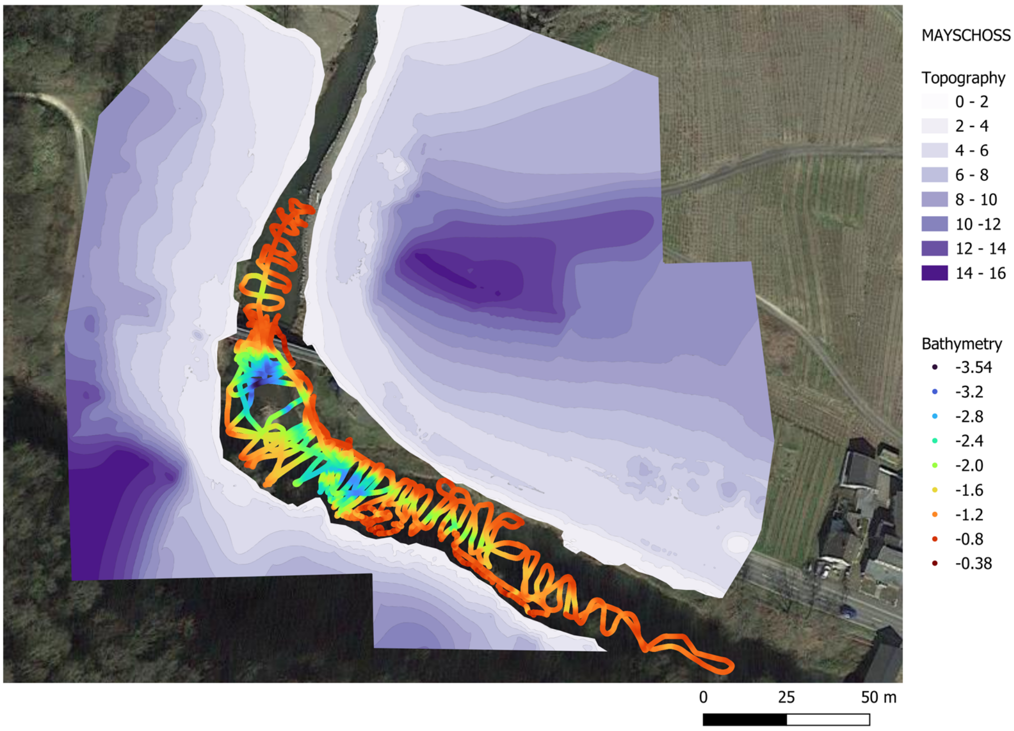

Figure 6. Digital terrain model (purple colors in meters) and bathymetry measured by the Z-boat single beam echo sounder (hot-cold colors in meters).

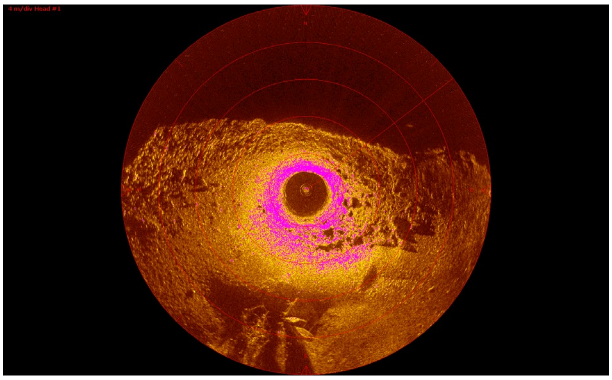

Figure 8. Side scan sonar image showing the contour of the river bank on top, cobbls and boulder on top of finer grained sediments, and bridge debris beams connecting with the river bed on the bottom of the image.

since just little motion of the boat during scans led to distortion of the images. During later deployments at different sites, it was found feasible to place the tripod tower on the riverbed even from an inflatable vessel which led to easier collection of data and better data quality.

The chirp sonar could only be deployed in the deeper sections of the river (> 1m), while also navigating around the bridge debris. This limited the data collection, but the team was able to record a transect including the scour hole at the base of the bridge debris which confirmed a scour hole of >3m depth (Fig. 9). Interestingly, the chirp sonar scan did not suggest major infill of the scour hole despite the presence of the nearby inner meander shoal with significant fine-grained sediment deposits.

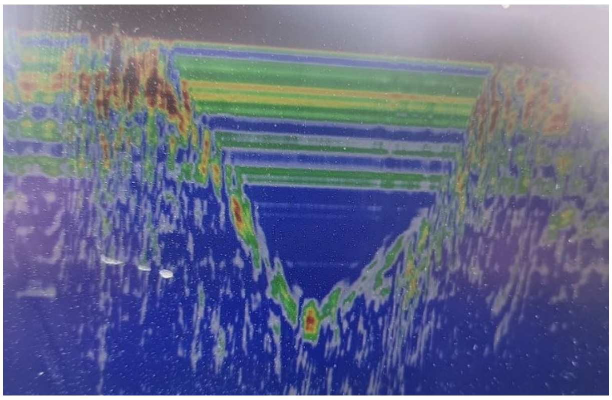

Figure 9. Chirp sonar transect showing scour hole with little to no infill. It also suggests that the scour hole is shaped of finer-grained materials and that only few cobbles rolled into the scour hole.

3.2. Portable free fall penetrometer deployments and sediment sampling

Portable free fall penetrometer (PFFP) deployments were performed avoiding areas of obvious presence of cobbles. In some cases, the PFFP still impacted with cobbles, leading to no penetration and to the only result that there was a cobble present. Therefore, PFFP results were mostly interesting along the fine-grained sediment deposits on the inner bend shoal. Figure 10 shows three example results. Fig. 10 (left) suggests the presence of gravel at the surface but still a soft and fine-grained sediment layer of ~ 3 cm. Moving further onto the shoal (Fig. 10 center and right), a clearly distinguishable fine-grained and soft sediment layer is profiled with a thickness of 10-14 cm above gravelly and coarser-grained substratum. Considering the spatial extent of the shoal, it suggests a significant volume of unconsolidated fine-grained flood deposits.

Sediment samples suggested a median grain size of fine-grained flood deposits sampled on the inner bend shoal of 0.12-0.15 mm with a fines content of approximately 30%.

4. Concluding remarks

Site characterization in dynamic ultra-shallow water depth (≲ 1m) environments can be challenging since neither onshore nor offshore technologies are typically designed to accommodate those conditions. However, there are many examples in coastal and riverine areas where those environments and the site investigation thereof are of utmost importance. Here, an example related to flood reconnaissance and infrastructure failure forensics is presented. Recent developments in geotechnical and geophysical surveying technology enhances feasibility and quality of data collections in these environments. Fusion of such data sets enables to conduct a detailed site investigation in a safe and efficient manner.

In this example, geoacoustic methods, namely single beam echo sounding, side scan sonar, and chirp sonar, were employed for bathymetric mapping, riverbed-infrastructure structure debris imaging, and scour hole riverbed characterization. The bathymetry was integrated into digital terrain models obtained from unmanned aerial vehicle surveying to derive a full terrain-bathymetry-model of the area highlighting channel and scour hole formations. Side scan riverbed imagery can be fused with satellite images to create a full above-water and under-water picture highlighting changes in riverbed sediment type and infrastructure debris-riverbed contact. Chirp sonar could only be deployed in sections of water depths > 1m. Nevertheless, it enabled to explore the scour hole further and confirmed the lack of infill despite significant flood deposits nearby. Deeper riverbed stratigraphy could not be resolved due to the coarseness of surface sediments (often cobbles and coarse gravel).

Geotechnical testing was performed using a portable free fall penetrometer. The probe proved rugged and reliable in the presence of even unexpected cobbles and debris in some locations, served the purpose of validating riverbed sediment maps from side scan sonar, and enabled to characterize the fine-grained to sandy sediments in more detail. Specifically, it allowed to measure layering of flood deposits in a convenient way. The data was augmented by sediment samples that enabled detailed classification of the flood deposits.

Fusion of geotechnical and geophysical data sets will enable new insights into sediment dynamics and soil mechanics in dynamic ultra-shallow aquatic

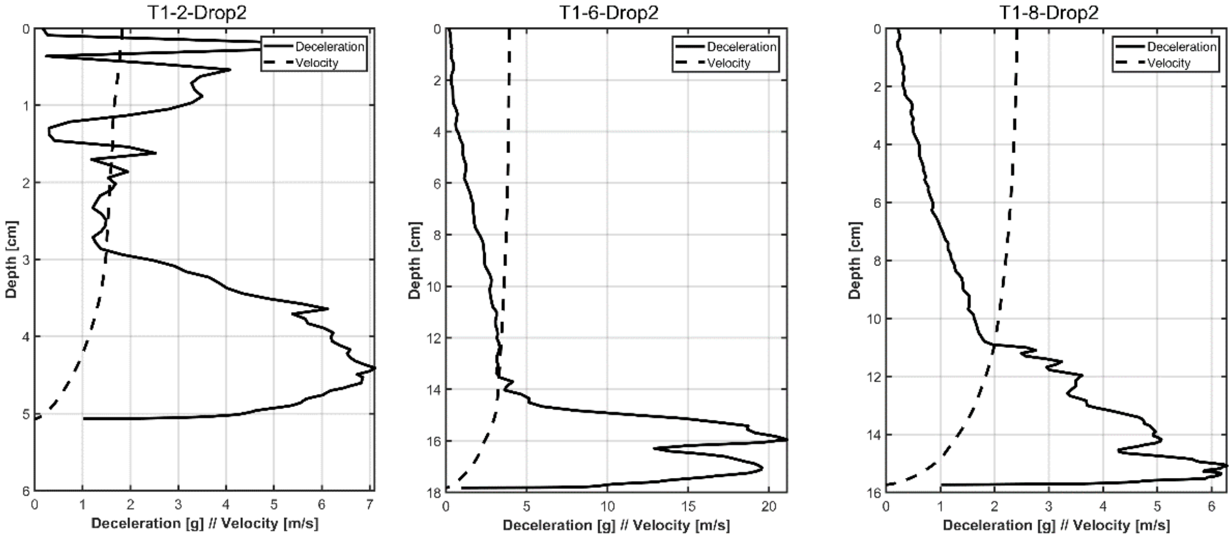

Figure 10. Three examples of portable free fall penetrometer profiles recorded along the area of the fine-grained sediment deposits on the inner bend shoal. The profiles show the measured deceleration of the probe after impacting the riverbed and the derived velocity (from single integration of deceleration) against penetration depth.

environments, as well as serve the purpose of improving reliability, safety, and efficiency of site investigation in such environments.

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