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Frequency domain electromagnetic induction survey in the intertidal zone: Limitations of low-induction-number and depth of exploration

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ABSTRACT

Subsurface investigation in the Belgian intertidal zone is severely complicated due to high heterogeneity and tides. Near-surface geophysical techniques can offer assistance since they allow fast surveying and collection of high spatial density data and frequency domain electromagnetic induction (EMI) was chosen for archaeological prospection on the Belgian shore. However, in the intertidal zone the effects of extreme salinity compromise validity of low-induction-number (LIN) approximated EMI data. In this paper, the effects of incursion of seawater on multi-receiver EMI data are investigated by means of survey results, field observations, cone penetration tests and in-situ electrical conductivity measurements. The consequences of LIN approximation breakdown were researched. Reduced depth of investigation of the quadrature-phase (Qu) response and a complex interpretation of the in-phase response were confirmed. Nonetheless, a high signal-to-noise ratio of the Qu response and viable data with regard to shallow subsurface investigation were also evidenced, allowing subsurface investigation in the intertidal zone.

1. Introduction

The coastal plain of Belgium is situated along the southern part of the North Sea and consists of polders, dunes and a shore. The western part of the Belgian coastal plain bears a thick Holocene sequence which is made up of alternating clastic and biogenic layers that are not consolidated (Baeteman, 1991). Besides the influence of natural processes on the subsurface, human intervention has been established as an important factor. Regarding human intervention in the coastal plain the industrial activities in pre-Roman and Roman times are of special interest due to intensive peat extraction and saltmaking (van den Broeke, 1996).

Conventionally, archaeological site investigation in the intertidal zone in Belgium has relied solely on information derived from boreholes, trenches, surface findings and (aerial) photographs. In the past visual observation of archaeological traces and surface findings have been most successful following storm surges which were powerful enough to remove sediment overlying deposits of archaeological interest. At present this is often no longer possible because many groynes were constructed in the seventies of the last century to halt excessive sediment erosion of beach sands by longshore currents. Thus archaeological traces often remain buried.

Invasive exploration in the intertidal zone is complicated due to a high groundwater table, strong groundwater flow, presence of loose sand, semi-diurnal tides and multiple tidal constituents. Because archaeological zones of interest are only approximately delineated and semi-diurnal tides occur, the ability to gather high resolution spatial data in a rapid manner is desirable. Additionally the occurrence of unexploded ordnances of both world wars poses a potential hazard and investigation would be preferably non-invasive. Several geophysical techniques are then eligible, yet the saline character of the intertidal zone is again a restricting factor. For example, ground penetrating radar does not work well in saline/brackish coastal environments because of signal dissipation and loss (Buyvenich et al., 2009). The viability of electromagnetic induction (EMI) data is also doubtful when using low-induction-number (LIN) approximation because of a limited dynamic range (Callegary et al., 2007; McNeill, 1980). Yet EMI has been successfully employed for the delineation of traces of archaeological interest (Simpson et al., 2009a) and assessment of palaeo-landscapes (De Smedt et al., 2011) in various geological settings. Moreover, EMI sensors have been used as a soil salinity sensor (e.g. de Jong et al., 1979; Hendrickx et al., 1992; Williams and Baker, 1982).

In this paper, the effects of incursion of seawater are discussed together with the viability of EMI as a prospection technique in the intertidal zone. The influence of extreme salinity on the responses of the sensor is investigated. Concerns such as biased data because of LIN approximation and uncertainty of the depth of investigation are researched as well. Results are validated with information from

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augerings, cone penetration tests (CPT) and in-situ electrical conductivity measurements.

2. Study area

The study area is located in the intertidal zone, near Raversijde, Belgium (Fig. 1) and is about 8 ha in size. The survey zone was demarcated by the sea during neap tide to the Northwest, by the levee to the Southeast and by groynes laterally. The beach has a low-angle dip with a mean slope of about 1.7%. Fig. 1B shows the elevation (mTAW, where TAW stands for "Tweede Algemene Waterpassing") of the study area. 0 mTAW is the Belgian reference datum level referring to the mean low low sea-water level.

The subsurface consists of Quaternary deposits comprised of clastic (beach sands and fine-grained mudflat sediments) and biogenic (peat) deposits which overlie Pleistocene deposits. The site was chosen for archaeological prospection mainly because of evidence of past peat extraction; an oblique aerial photograph taken after a storm event and before the construction of the groynes revealed traces thereof. Orthorectification and georeferencing of this photograph was performed (Fig. 1C). Controlled detonation of shells after burying has taken place near the low water line in the study area from the late 90s until recently. Unfortunately, information about quantity and exact locations is not available.

3. Materials and methods

3.1. EMI

EMI instruments produce a time-varying electromagnetic (EM) field, thereby inducing EM fields in the subsurface and measure the resulting field, which has a quadrature-phase (Qu) component and in-phase (Ph) component, expressed in parts per thousand.

The Qu response is converted to ECa, expressed as mS m^{-1}, using the formula (McNeill, 1980):

$$\mathrm{ECa} = \frac{2}{\pi f s^2 \mu_0} \cdot \left(\frac{\mathbf{H}_s}{\mathbf{H}_p}\right)_{\mathrm{Qu}}$$

where f is the frequency (Hz), s is the coil separation (m), μ_0 is the magnetic permeability of free space ($4\,\pi\,10^{-7}$ H/m) and $(\mathbf{H}_s\,/\,\mathbf{H}_p)_{\mathrm{Qu}}$ is the Qu component of the secondary $\mathbf{H}_s$ to primary $\mathbf{H}_p$ magnetic field coupling ratio. The formula is an approximation based on the assumption of operating the instrument in a LIN environment with zero instrument elevation. ECa as used throughout this article therefore denotes LIN approximated ECa. The dimensionless induction number is defined as the ratio of the instrument coil separation divided by the skin depth δ. The skin-depth in turn is defined as the distance within a half-space wherein a plane wave is attenuated by 1/e (37%) of the value at the surface (Spies, 1989). As the true conductivity increases, the skin depth decreases causing the induction number to rise. This effect is enhanced with increasing intercoil spacing. At high values of true conductivity the Qu response is then no longer linearly proportional to true conductivity. ECa becomes biased as the true conductivity is increasingly underestimated for a given frequency and intercoil spacing (McNeill, 1980). It has been demonstrated that, as a consequence, there is a potential risk for spatially distorted data in high conductivity environments (Beamish, 2011). However, it is unclear what the upper boundary of the induction number for a valid LIN approximation should be (Callegary et al., 2007; McNeill, 1980). Beamish (2011) notes that such discussions are not generally useful unless the coil configuration,

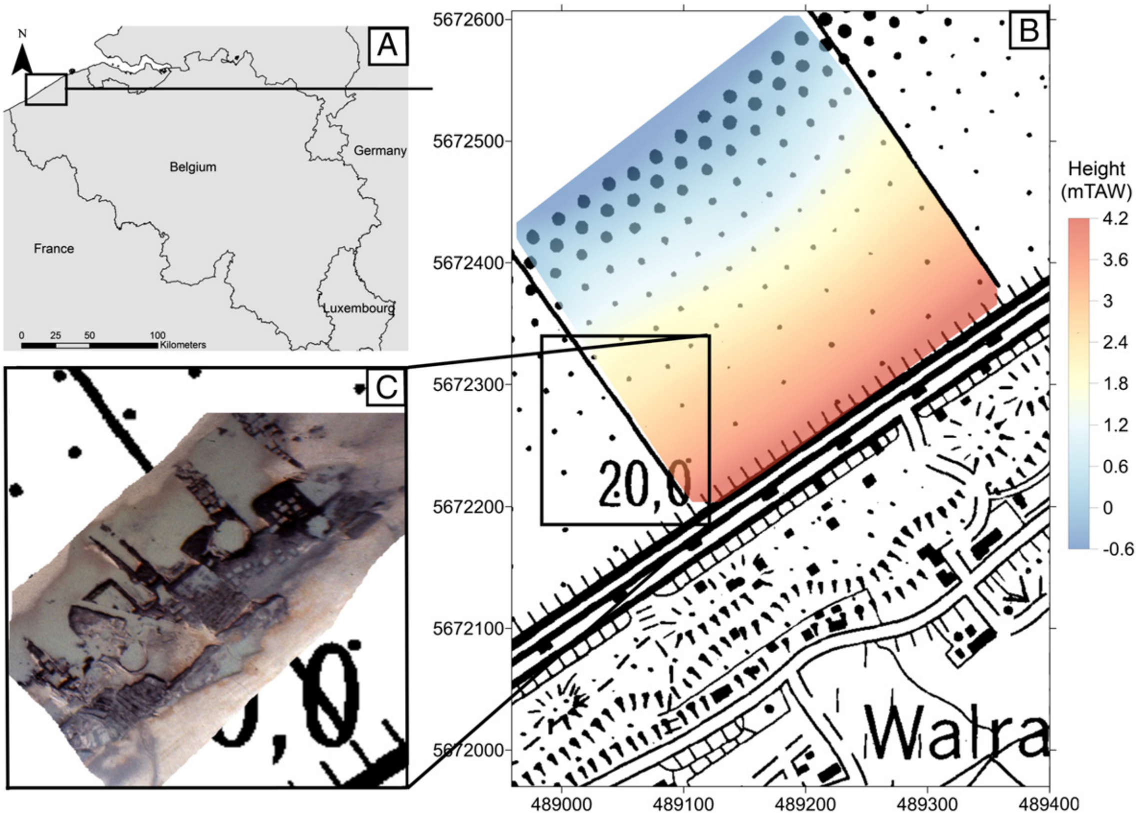

Fig. 1. (A) Location of the study area in Belgium. (B) Localization on the topographical map with elevation of the study area, coordinates are in the UTM geographic coordinate system (m). (C) Orthorectified aerial picture taken after a storm event at low tide with a view of different peat excavation features present in the subsurface (author: Etienne Cools, early 1970s, unpublished). The clipped toponym 'Walra' is 'Walraversijde' in full.