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A new radiometric instrument for *in situ* measurements of physical sediment properties

W. Jacobs[A,E], *M. Eelkema*[A], *H. Limburg*[B] *and J. C. Winterwerp*[C,D]

[A]Delft University of Technology, Faculty of Civil Engineering and Geosciences, Hydraulic Engineering Section, PO Box 5048, 2600 GA Delft, The Netherlands.
[B]Medusa Explorations B.V., PO Box 623, 9700 AP Groningen, The Netherlands.
[C]Delft University of Technology, Faculty of Civil Engineering and Geosciences, Environmental Fluid Mechanics Section, PO Box 5048, 2628 CN Delft, The Netherlands.
[D]Deltares, PO Box 177, 2600 MH Delft, The Netherlands.
[E]Corresponding author. Email: walterjacobs@hotmail.com

Abstract. Information on the sedimentological composition of sediment beds in marine wetlands is important for the study of the complicated interactions between physical, biological and chemical processes. *In situ* soil sample collection and subsequent laboratory analyses using traditional methods is rather time consuming. The present paper presents the Medusa (Multi Detector system for Underwater Sediment Activity) RhoC system. 'Rho' refers to density and 'C' to the activity concentration of the decaying isotopes adhered to the sediments. The new instrument directly translates (the attenuation of) natural radioactivity to sedimentological data concerning the depth-averaged sediment composition and vertical density profiles of the upper 15 cm of the sediment bed. The accuracy and applicability of the instrument were assessed to illustrate its potential and limitations. Results from a field campaign on several intertidal flats and from similar measurements in the laboratory for controlled circumstances were compared with data obtained by traditional analyses. The instrument generates accurate results for the depth-averaged sediment composition. Vertical density profiles are also well represented by the RhoC after smoothing and correcting the data for partly saturated soils. Thus, Medusa RhoC is a useful and practical tool to provide accurate sedimentological data in a fast and cost-effective way. The combination of sedimentological relations with the data obtained by RhoC further increases the applicability of the new instrument.

Additional keywords: clay, cohesive sediment, intertidal, mud, natural radioactivity, sand, Western Scheldt Estuary.

Introduction

Information on the sedimentological composition (sand content ξ_{sa} (%) and mud content ξ_{mu} (%)) and bulk density (ρ_{bulk} (kg m^{-3})) of sediment beds in marine wetlands is important for the study of the complicated interactions between physical, biological and chemical processes (e.g. Widdows and Brinsley 2002; Winterwerp and Van Kesteren 2004). The horizontal and vertical distributions of sediment properties in combination with the prevailing forcing conditions characterise these interactions.

Information on sediment properties enables the study of these interactions and functions as input information for numerical model simulations. Sedimentological data are usually obtained by *in situ* soil sample collection and subsequent laboratory analyses using traditional methods, which are time consuming and costly. Alternative methods are currently under development. An example is remote sensing (using aircraft or satellites), which uses the amount of backscatter of transmitted radar, laser or acoustic pulses. However, these techniques only characterise the composition of the surface layer of sediment beds (e.g. Eleveld 1999; Van der Wal *et al.* 2005), whereas the vertical distribution of sediment properties is important for the study of (morphological) processes.

Recently, radiometric sedimentology has been used to characterise sediment components using the concentration of natural γ rays emitting radionuclides. The relationship between the concentration of radioactive isotopes and the sediment composition forms the radiometric fingerprint. Sediments with a different fingerprint can be radiometrically distinguished, which enables characterisation of the sediment composition (De Meijer and Donoghue 1995; Gouleau *et al.* 2000; Herman *et al.* 2001). An existing measuring system based on radiometric sedimentology is the Medusa (Multi Detector system for Underwater Sediment Activity) system (Koomans 2001; Roberti 2001; De Groot *et al.* 2002; Van Wijngaarden *et al.* 2002*a*, 2002*b*). This system is towed behind a ship and weighs ~30 kg. It consists of a γ-ray detector to measure the energy of natural γ rays, which are subsequently translated into a depth-averaged sediment composition. The depth for which the average composition is determined increases with decreasing bed density. However, both the depth-averaged sediment composition and the packing density are required to qualify and quantify characteristic bulk sediment properties for processes in the sediment bed (e.g. Winterwerp and van Kesteren 2004; Jacobs *et al.* 2007*a*, 2007*b*).

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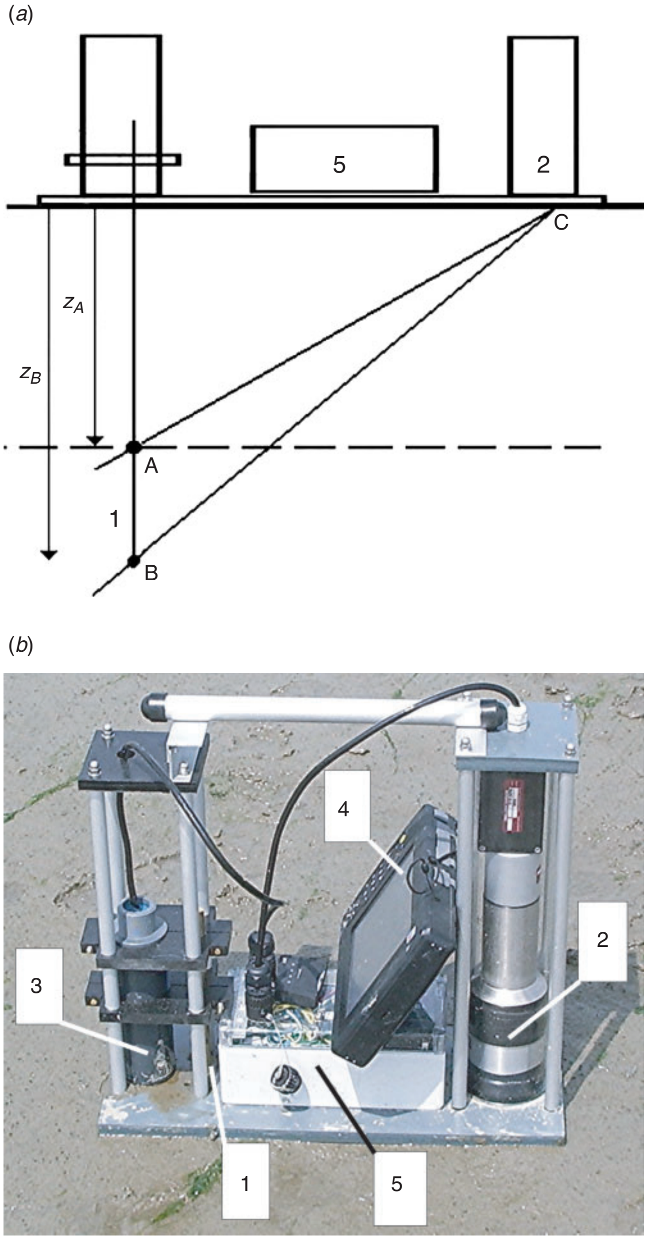

Fig. 1. (*a*) Schematic depiction and (*b*) photograph of the Medusa RhoC system showing (1) the ^{22}Na source, (2) the γ-ray detector, (3) the time domain reflectometry (TDR) sensor, (4) the notebook and (5) the data logger, GPS and power supply. The upper panel indicates varying positions of the ^{22}Na source below the surface of the sediment bed (z_A and z_B) in relation to the position of the γ-ray detector ('C'). 'AC' and 'BC' reflect different path lengths over which ρ_{bulk} is measured. The TDR sensor and ^{22}Na source are coupled and are jointly moved upward and downward.

A new and more practical handheld (~8 kg) version of the Medusa system has been deployed: the 'Medusa RhoC' system (Fig. 1). 'Rho' refers to density and C (Bq kg^{-3}) refers to the activity concentration of decaying isotopes per unit mass of sediment. The system determines the depth-averaged sediment composition and vertical profiles of ρ_{bulk} and the water content of the upper 15–20 cm of the sediment bed. The individual components of the system are calibrated for laboratory conditions (Tijs 2007). However, calibration of the complete system, the practical field applicability for intertidal flats and the accuracy and operating speed of the new instrument in relation to traditional methods have not yet been examined.

The aim of the current paper was to illustrate the potential and limitations of the new instrument. Three objectives were formulated. First, the accuracy of the Medusa RhoC data concerning sediment composition and ρ_{bulk} was checked by evaluating data from an extensive field campaign. The data were compared with the results of traditional laboratory analyses, as well as with the results obtained by Medusa RhoC in a laboratory set up. The second objective was to assess the practical applicability of the new instrument with regard to the duration of the measurement procedure in relation to traditional methods. The third objective was to check the existence of already published sedimentological relationships. The combination of these relationships with data obtained by the new instrument can significantly increase its applicability. The current study was partly based on field and laboratory data described in Eelkema (2008).

Theory

Sedimentology

Sediment fractions are often characterised by their individual mass content relative to the total dry mass of a soil sample (ξ_i (%)). The most common fractions in wetlands are sand ($\xi_{sa} > 63\,\mu$m), silt ($2\,\mu\text{m} < \xi_{si} < 63\,\mu$m) and clay ($\xi_{cl} < 2\,\mu$m). Mud ($\xi_{mu} < 63\,\mu$m) is a mixture of clay, silt and organic matter (ξ_{om}). The latter exhibits a wide range of particle sizes. The specific surface area of clay minerals characterises its cohesive properties and, consequently, its capacity to bind water and organic material. The latter implies that the properties of mud flocs are strongly related to the specific surface area of the clay particles. The clay fraction in each marine system exhibits a unique mixture of clay minerals, which indicates specific relationships between ξ_{cl} and ξ_{si} (Flemming 2000), ξ_{cl} and ξ_{om} (Hedges and Keil 1995; Middelburg and Herman 2007) and ξ_{cl} and ρ_{bulk} (Flemming and Delafontaine 2000).

A measure for cohesiveness is the plasticity index (*PI* (%)), which is the water content (*W* (%), i.e. mass of water in relation to the total dry mass of solids) for which a soil exhibits plastic behaviour. The *PI* follows from the Atterberg limits (Skempton 1965), which are commonly used in geotechnical engineering to characterise soil mechanical behaviour (e.g. Mitchell 1976; Jacobs *et al.* 2007*a*, 2007*b*). The *PI* of a 100% clay mixture varies considerably (1–10) with varying clay mineralogy, the presence and type of organic material (e.g. EPS, extracellular polymeric substance) and pore water chemistry. Another important bulk parameter to characterise sediment behaviour is ρ_{bulk}:

$$\rho_{bulk} = Sn\rho_w + (1 - n)\rho_{sed} \tag{1}$$

where S (–) is the degree of saturation (i.e. the volume of water in relation to the volume of pores), n (%) is the porosity, ρ_w (kg m^{-3}) is the density of water and ρ_{sed} (kg m^{-3}) is the specific density of sediments (≈2650 kg m^{-3}).

Radiometric sedimentology

The energy of γ rays ($E\gamma$ (eV)) is directly and uniquely related to the isotope that released the ray. The amount of radioactive material is an indicator of the sediment composition, as natural fine sediments contain specific mixtures of radioactive isotopes (^{40}K, ^{232}Th and ^{238}U; e.g. Van der Graaf *et al.* 2007). The latter isotopes, in particular, adhere to fine sediments. The sediment fingerprint is the relationship between C and the grain size distribution. Fingerprints are site specific as the clay fraction in a marine system exhibits a specific mineralogical composition and, therefore, a specific number of adhered isotopes (Venema and De Meijer 2001). The latter is more or less constant for an individual marine system, but may vary slightly owing to a combined marine and fluvial input of fine sediment. This indicates that the required number of fingerprints to calibrate natural radiation depends on the size of the study area.

γ radiation interacts with atoms by means of Compton scattering and photoelectric absorption when penetrating a medium (Koomans 2001). These interactions result in attenuation of $E\gamma$; the degree of attenuation depends on the number of atoms per unit volume and on the distance travelled through a medium (e.g. Hussein 2003*a*, 2003*b*). When path length and the attenuation coefficient are constant, the attenuation of γ radiation depends only on ρ_{bulk}. The latter illustrates the applicability of γ radiation for the determination of soil density.

Materials and methods

Medusa RhoC

The Medusa RhoC instrument holds a γ-ray detector (caesium iodine scintillation crystal and photomultiplier), a γ-ray source (^{22}Na), a time-domain reflectometry (TDR) sensor, a GPS, a power supply (12 V battery) and a data logger (Fig. 1). The dimensions of the system are 20 cm × 50 cm × 50 cm, for the width, length and height respectively. The system is (wireless) connected to a notebook computer and can be operated non-stop for 8–10 h.

A small radioactive ^{22}Na source was placed in the tip of a brass rod with a diameter of 1 cm and a length of 20 cm. This rod was pushed downward into the sediment bed before starting a measurement. The attenuation of $E\gamma$ between the ^{22}Na source and the detector is related to ρ_{bulk}. The vertical position of the rod was automatically recorded. The ^{22}Na source released γ rays with an energy level comparable to the natural radioactivity of the sediments; special permits to operate and transport the instrument are not required. The TDR sensor derived the dielectric constant of a soil from the travel time of an electromagnetic wave that propagated along two metallic rods. This constant related to W only because it was independent of ρ_{bulk}, temperature, salinity or mineral composition (Tijs 2007). The TDR sensor and ^{22}Na source are jointly inserted into the sediment bed.

Energy spectrum analysis

The detector translated the energy of the γ rays released by natural isotopes and by the ^{22}Na source into C. Tijs (2007) and Eelkema (2008) give a comprehensive description of both translation procedures, which we will summarize here. The comparison of C with a previously determined radiometric fingerprint of a representative number of soil samples generated the sediment composition (ξ_{sa} and ξ_{mu}). This representative number is discussed in the present paper.

The energy spectrum of ^{22}Na could easily be distinguished from natural isotopes (Tijs 2007). Furthermore, this spectrum was elevated in relation to the spectrum generated by natural radiation. This elevation depended on the attenuation of $E\gamma$ between source and detector and, therefore, was related to the travelled path length and ρ_{bulk}. Tijs (2007) calibrated the relationship between elevation and ρ_{bulk} for a laboratory set up consisting of a water-filled box with a varying number of glass plates (identical specific density as sediment).

The bulk activity concentration (C_{bulk} (Bq kg^{-1})) for a known path length followed from the elevated energy spectrum. However, not only solids, but also water attenuated $E\gamma$. Therefore, C_{bulk} had to be corrected for the presence of water to obtain C for solids only (C_{solids} (Bq kg^{-1})):

$$C_{solids} = C_{bulk}(1 + W) \tag{2}$$

W was measured using the TDR sensor. Eqn (2) was required to determine both ρ_{bulk} and the sediment composition because γ rays released by both the ^{22}Na source and the sediments were attenuated by pore water.

A varying vertical position of the ^{22}Na source generated varying path lengths between the source and the detector. Radiation intensity decreased with the inverse of the squared path length. When varying the position of the source along a vertical axis directly below the detector, the range of detected radiation intensity was too large to derive accurate ρ_{bulk}. Therefore, the position of the source was varied along a vertical axis at 40 cm from the detector (Fig. 1). In this way, the variation of the path length and, therefore, the variation of radiation intensity between the source and the detector was significantly smaller. To determine ρ_{bulk} in a specific position along this axis, the following formulation was proposed:

$$\overline{\rho}_{AB} = \frac{\overline{\rho}_{BC} z_B - \overline{\rho}_{AC} z_A}{z_B - z_A} \tag{3}$$

where $\overline{\rho}_{AB}$ (kg m^{-3}) is the average density between 'A' and 'B', $\overline{\rho}_{AC}$ (kg m^{-3}) and $\overline{\rho}_{BC}$ (kg m^{-3}) are the average densities along the trajectories 'AC' and 'BC', and z_A (m) and z_B (m) are the vertical positions of 'A' and 'B' below the sediment–water interface.

Measurement procedures

A typical measurement started by pushing the ^{22}Na source and TDR sensor jointly into the sediment bed to a depth of ~15 cm. Next, the depth-averaged sediment composition was determined. The duration of this measurement was set by the duration required to distinguish between background radiation (e.g. cosmic radiation) on the one hand and natural radiation from sediments on the other. Simultaneously, ρ_{bulk}, W, depth and GPS coordinates were recorded. In the second phase of the measurement, the ^{22}Na source and TDR sensor were pulled upward step by step. W and ρ_{bulk} were determined for each step. In the current study, we applied a vertical resolution of six to eight points, with a mutual distance of 2–3 cm.

As the current study discusses the testing and calibration of Medusa RhoC, multiple sediment cores with a length of 20 cm were collected close to each measurement station. The

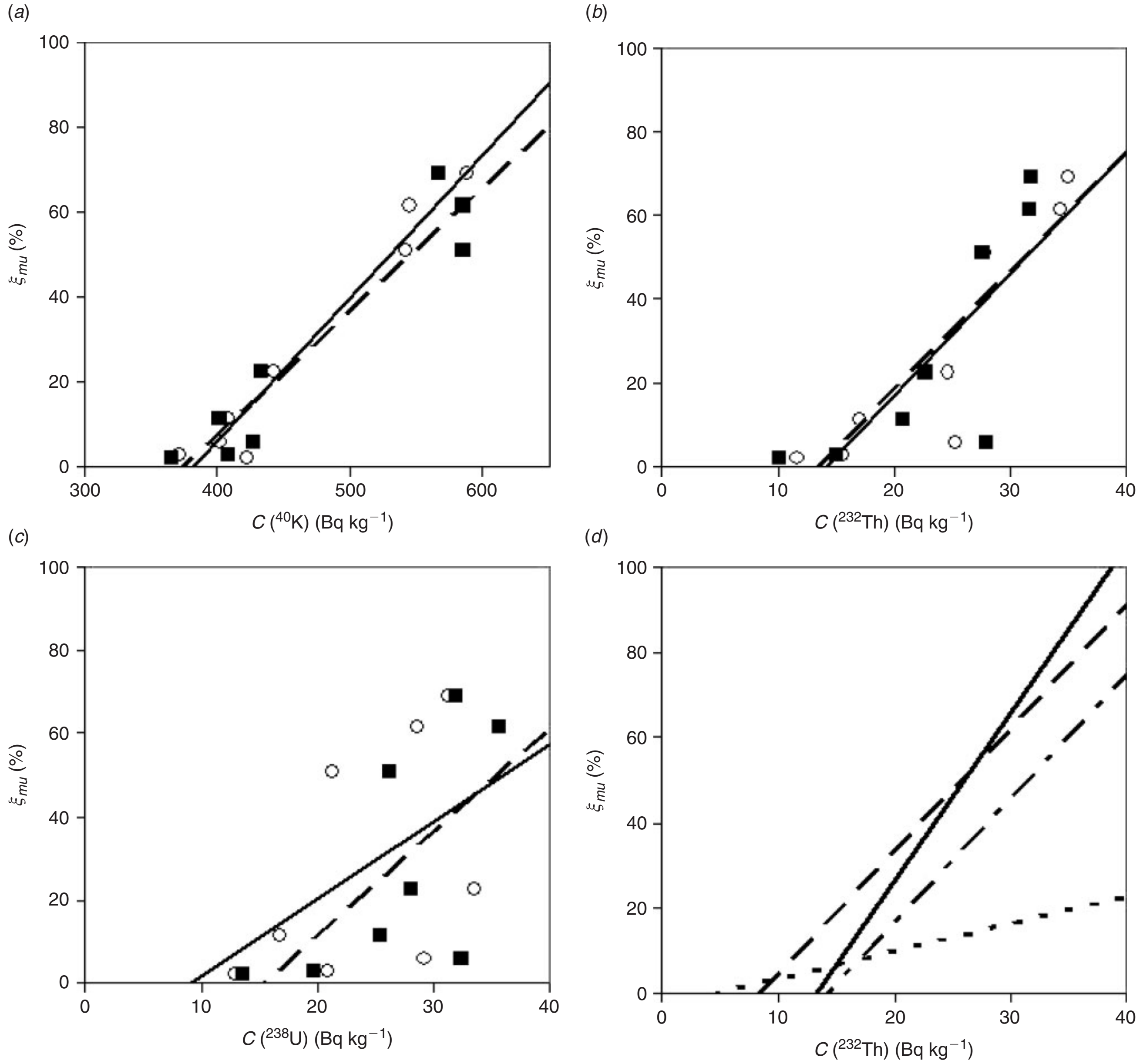

Fig. 2. Mud content (ξ_{mu}) as a function of C measured in the field and in the laboratory by RhoC for the isotopes (*a*) ^{40}K, (*b*) ^{232}Th and (*c*) ^{238}U for sediments of the Saeftinghe tidal flat. Laboratory fingerprints are indicated by the dashed lines (■) and field fingerprints are indicated by the continuous lines (○). (*d*) The ^{232}Th fingerprints following laboratory analyses and RhoC field data are compared for Walsoorden (continuous line), Molenplaat (dashed line), Valkenisse (dotted line) and Saeftinghe (dash-dotted line).

cores were carefully extracted and transported in a cooler box to avoid disturbance of the sediment properties and to minimise ongoing biological activity. C, PI, n_{sasi}, W, ρ_{bulk}, dry density (ρ_{dry} (kg m^{-3})), S, ξ_{sa}, ξ_{si}, ξ_{cl} and ξ_{om} were subsequently determined in the laboratory using traditional methods (e.g. Head 1980). These methods included freezing, slicing, freeze drying, weighing and determination of grain size analyses (using a Malvern Mastersizer 2000; Malvern Instruments Ltd, Worcestershire, UK) and carbon contents.

The above properties were determined with a similar resolution to the Medusa RhoC measurements. C and PI were determined for complete cores. The PI was determined according to a geotechnical standard (ASTM D4318). The C (of dry material) was measured in a laboratory for controlled circumstances using a similar detector to that mounted on the Medusa RhoC. Both the detector and the soil sample were placed in a box with a 10-cm thick lead shielding to exclude background radiation during the measurement.

Field site and laboratory set up

The laboratory set up to test RhoC for controlled circumstances consisted of a wooden box (80 cm × 50 cm × 25 cm) filled with varying mixtures of sand and silt for both saturated ($S = 1$) and dry ($S = 0$) conditions (Eelkema 2008). The field site contained four tidal flats (within a range of 15 km) in the Western Scheldt Estuary in The Netherlands (51.04–51.81°N; 3.23–4.39°E): Molenplaat, Walsoorden, Saeftinghe and Valkenisse (listed in the upstream direction). The Saeftinghe flat is the muddiest and the Valkenisse flat the sandiest. The mineralogical composition varied slightly along the estuary, but mainly consisted of illite and smectite, with smaller amounts of kaolinite and chlorite (Fontaine 2004). The measurement stations (35 in total) were located on five transects ranging from predominantly sandy to muddy sediments.

Results

Practical applicability

Determination of the depth-averaged sediment composition at each measuring station took ~15–20 min. Variation in the duration depended on the characteristics of the sediment bed. Sandy soils contain fewer isotopes than muddy soils and a slightly longer measurement duration is required to obtain a similar degree of accuracy. Laboratory tests indicate that ρ_{bulk} data converge to a constant value after ~35 s. Within this period, W is also accurately determined. The total duration of a ρ_{bulk} and W measurement in one position (z) takes ~1 min, including the time required to reposition the TDR sensor and ^{22}Na source vertically. The total measurement procedure at one measuring station depends on the vertical resolution of the measurements. The current study applied a vertical resolution of six to eight measuring points, which leads to a total measurement time of ~20–30 min (i.e. 15–20 min for the composition and 6–8 × 1 min for a density profile). Both the collection of sediment cores and the repositioning to a new measuring station took ~15 min.

Traditional laboratory analyses of the sediment cores collected at the 35 measuring stations concerning W, ρ_{bulk}, ρ_{dry}, S, ξ_{sa}, ξ_{si}, ξ_{cl} and ξ_{om} were executed by a single person and took ~2 months. The determination of a fingerprint (C and a grain size analysis) took ~1 h for one sample. In the current study, a fingerprint for all stations was determined to evaluate the accuracy at each measuring station.

The TDR sensor malfunctioned during the laboratory and field measurements as a result of hardware problems. However, the sensor is a standard device and suitable for the determination of W of intertidal sediment beds according to the supplier. W derived from the laboratory analyses of the cores was used to determine the sediment composition and ρ_{bulk}.

Sediment composition

A selection of the sediment composition and ρ_{bulk} results as measured by Medusa RhoC is presented. Eelkema (2008) shows all results of the RhoC measurements and laboratory analyses. Fig. 2 shows typical examples of the depth-averaged ξ_{mu} as a function of C of the isotopes ^{40}K, ^{232}Th and ^{238}U. The C measured in the field by RhoC and the C determined in the laboratory set up for dry sediment are shown. The effect of pore water is corrected using Eqn (2). The fitted lines are the actual fingerprints. The laboratory and field fingerprints for all isotopes exhibit identical correlation coefficients (Table 1). The correlation is less strong only for the Valkenisse flat. In addition, scattering of the fingerprints for ^{238}U is relatively large compared with ^{232}Th and ^{40}K.

Table 1. Comparison of the correlation coefficients (R^2) for the ^{232}Th fingerprints obtained in the laboratory and in the field by Medusa RhoC for all four tidal flats

	Molenplaat	Saeftinghe	Walsoorden	Valkenisse
Field	0.90	0.90	0.98	0.56
Laboratory	0.90	0.90	0.98	0.56

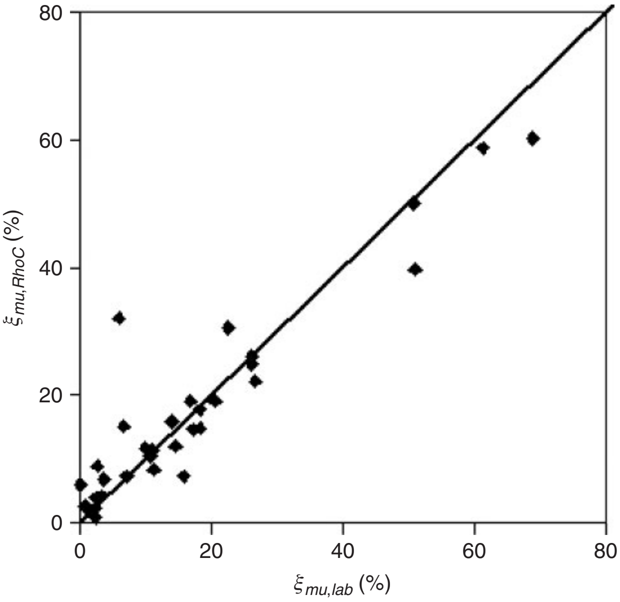

Fig. 3. Comparison between data obtained by RhoC (vertical axes) and by traditional laboratory analyses (horizontal axes) for depth-averaged mud content (ξ_{mu}). The continuous line is the line of perfect agreement. The correlation coefficient is $R^2 = 0.87$.

The relationship between ξ_{mu} and C for all flats exhibited the best correlation for ^{232}Th (Eelkema 2008). Therefore, this fingerprint was used to determine the sediment composition. Finally, the field fingerprints for ^{232}Th for all tidal flats were compared (Fig. 2*d*). The fingerprints for three of the four tidal flats were statistically comparable, as the differences were rather small. The fingerprint for the most upstream site, Valkenisse tidal flat, deviates from the other three. The three other flats exhibit larger ξ_{mu} than the Valkenisse flat. The correlation for results obtained by RhoC compared with traditional laboratory analyses for the depth-averaged ξ_{mu} is good ($R^2 = 0.87$; Fig. 3).

Bulk density

The minimum depth for the ^{22}Na source is 2.5 cm. For smaller depths, γ rays not only travel along the diagonal between the source and the detector, but also along the surface of the sediment bed. The latter hampers accurate translation of detected $E\gamma$ to ρ_{bulk}. Furthermore, the vertical ρ_{bulk} profiles following RhoC data in combination with Eqn (3) deviate in two ways from the profiles determined by the traditional analyses (Fig. 4).

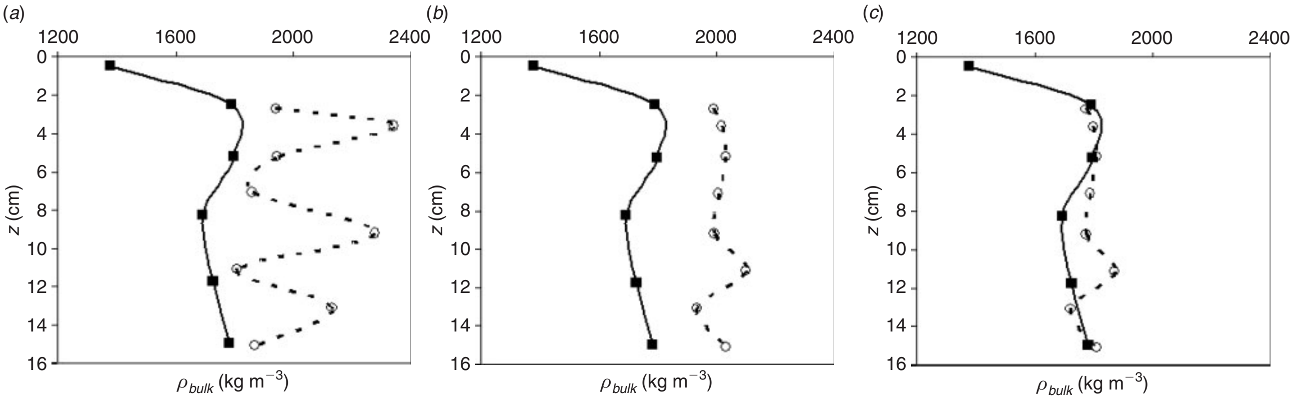

Fig. 4. Typical examples of vertical bulk density (ρ_{bulk}) profiles measured with RhoC (○, dashed line) and with traditional analyses (■, continuous line). The left panel (*a*) shows the initial results of RhoC following Eqn (3). An improved agreement occurs between the RhoC data and the data determined by traditional analyses when correcting data (*b*) using Eqn (4) for oscillations and (*c*) using Eqn (5) for both oscillations and offset.

First, results obtained by RhoC exhibit an oscillating character compared with the smoother laboratory profiles (Fig. 4*a*). Second, the RhoC results exhibit an offset in relation to the laboratory profiles (Fig. 4*b*). Similar behaviours were observed for all measurement stations (Eelkema 2008).

The latter two deviations indicate that the calculation of vertical ρ_{bulk} profiles derived from RhoC data is not satisfactory using Eqn (3) alone. We used a theoretical approach to understand and correct for the oscillations because no laboratory data are available for further analysis. The ρ_{bulk} measured by RhoC varied stochastically. The tests with the laboratory set up show that for similar conditions, RhoC produces some scattered results with a standard deviation of ~15 kg m^{-3}. This standard deviation, in combination with a random number generator, was used to generate input densities along the trajectories ‘AC’ and ‘BC’ (Fig. 1*a*) in Eqn (3).

Fig. 5 shows that the oscillations indicated in Fig. 4*a* are well reproduced by imposing this input. This leads to the conclusion that the random error of the measurement causes these oscillations. To minimise the effect of this random error, a method was proposed to derive smoother ρ_{bulk} profiles from the measurements of RhoC:

$$\rho(z_i) = \frac{\rho_{i-1} + \rho_i + \rho_{i+1}}{3} \tag{4}$$

where ρ_{i-1}, ρ_i and ρ_{i+1} (kg m^{-3}) are densities following Eqn (3), and z_i (m) is the depth of a measurement location. For the upper and lower points of the profiles, we applied a two-point interpolation only.

To understand the occurrence of the offset of ρ_{bulk}, we have evaluated our measuring procedures carefully. It is unlikely that its cause lies in measuring inaccuracies, sampling procedures, sample transport, storage and/or treatment. However, we found that the offset negatively correlated with S (Fig. 6):

$$\Delta\rho_{bulk} = aS + b \tag{5}$$

with a (= −8.2 kg m^{-3}) and b (= 859 kg m^{-3}) as empirical constants. We have no physical explanation for this negative correlation. Moreover, this offset and its relationship with S were not found for the laboratory tests (applying RhoC on artificially generated sand silt mixtures). Correcting ρ_{bulk} as measured by RhoC with Eqns (4) and (5) generates a good correlation ($R^2 = 0.77$) between $\rho_{bulk}(z)$ obtained by RhoC and $\rho_{bulk}(z)$ obtained by traditional methods (Fig. 7).

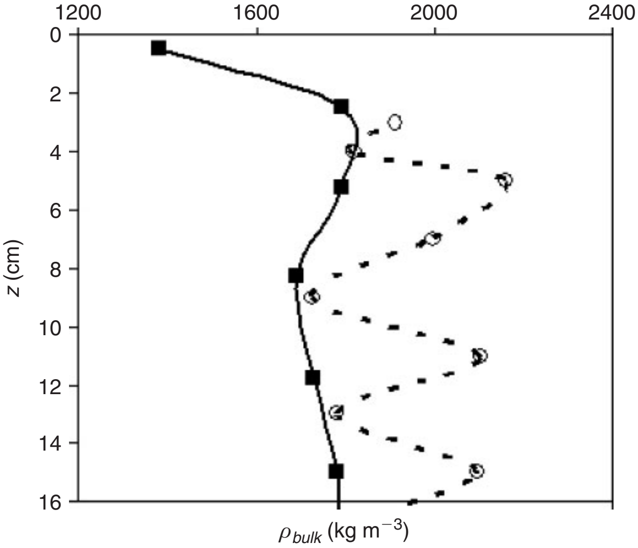

Fig. 5. Comparison of vertical bulk density (ρ_{bulk}) profiles following RhoC laboratory measurements (■, continuous line) and following simulations (○, dashed line). Simulated data follow from Eqn (3), with ρ_{bulk} obtained by traditional methods in combination with a random error as input. The character of the simulated data agrees with typically observed oscillations (e.g. Fig. 4*a*).

Sedimentological relationships

The third objective of the current study was to verify the existence of sedimentological relationships for sediments ranging from predominantly mud to sand. Results were derived from

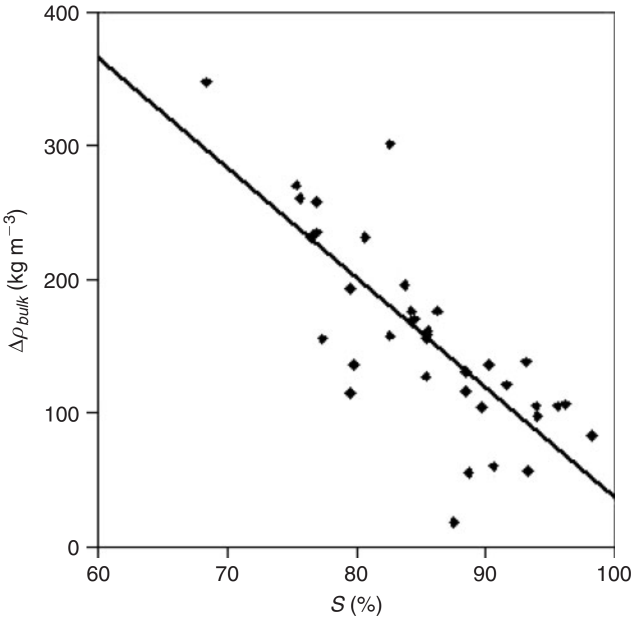

Fig. 6. Depth-averaged degree of saturation (S) for the cores as a function of the depth-averaged bulk density (ρ_{bulk}) offset. The latter offset is the difference between the depth-averaged ρ_{bulk} obtained by laboratory analyses and by RhoC. A positive offset indicates an overestimation of ρ_{bulk} by RhoC. The correlation coefficient is $R^2 = 0.60$.

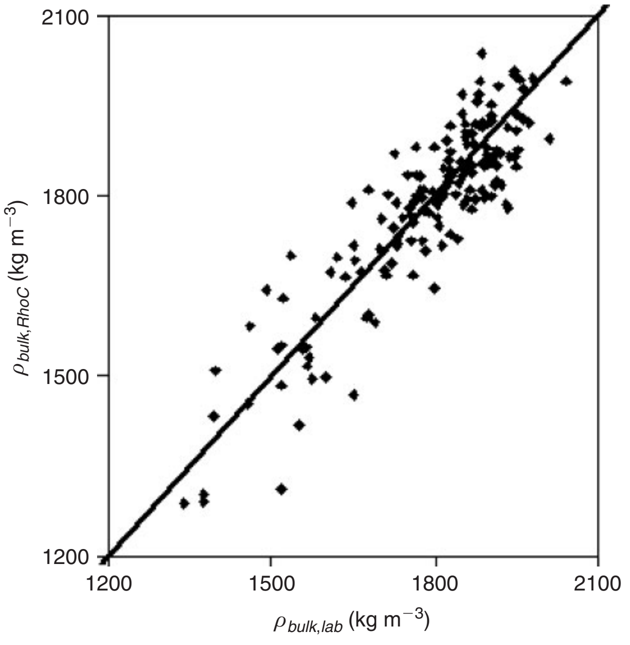

Fig. 7. Comparison between the bulk density, $\rho_{bulk}(z)$, obtained by RhoC (vertical axes) and by traditional laboratory analyses (horizontal axes). The continuous line is the line of perfect agreement. The correlation coefficient is $R^2 = 0.77$.

traditional laboratory analyses of the sediment cores. Fig. 8 shows clear relationships between ξ_{cl} and ξ_{si} (Fig. 8*a*) and between ξ_{om} and ξ_{mu} (Fig. 8*b*). A negative relationship exists between ξ_{mu} and ρ_{bulk} for soil samples for which $\xi_{mu} > 25\%$ (Fig. 8*c*). For granular samples ($\xi_{mu} < 25\%$), the scatter is significantly larger. Finally, *PI* was determined for a representative number of soil samples to show the relationship with ξ_{cl} (Fig. 8*d*). Differences in clay mineralogy and ξ_{om} are not incorporated. The slope of this relationship reflects the activity of the clay fraction and is ~6.

Discussion

The good agreement between the laboratory and field fingerprints using RhoC indicates that depth-averaged sediment composition is accurately predicted by the Medusa RhoC system. Koomans (2001) and Van Wijngaarden *et al.* (2002*a*, 2002*b*) reported similar results. The proposed methods for smoothing and correcting for the offset (i.e. overestimation of $\rho_{bulk}(z)$ by RhoC) that exists for partly saturated soils generates good results. However, the exact cause of the offset is not yet fully understood.

Fingerprints of different tidal flats vary slightly, most likely because of variations in clay mineralogy. Fontaine (2004) shows this variation for the Western Scheldt Estuary. However, variations in the clay mineralogy are too small to explain the markedly different fingerprint recorded for the Valkenisse flat. Possibly the more sandy character (low ξ_{cl}) of this flat in combination with the fact that isotopes, in particular, adhere to fine sediment generates a larger sensitivity to errors of the determination of ξ_{cl} for sandy soils. The relatively high level of scattering for ^{238}U was caused by the presence of feldspar (Koomans 2001).

The good agreement between the laboratory and field fingerprints further indicates that the detected natural radioactivity is representative for the upper 15 cm of the sediment bed. Van Wijngaarden *et al.* (2002*a*) used soil samples obtained from a layer with a similar thickness to determine the fingerprints (20 cm). The relationship between ρ_{bulk} and the actual depth for which the sediment composition is measured has not been examined. The latter depth decreases with increasing ρ_{bulk}, which may influence the results of RhoC if the sediment composition at depths below 10 cm varies significantly. However, Eelkema (2008) shows that the sediment composition of the field sites does not vary significantly below depths of ~5 cm.

The practical usage of Medusa RhoC in the field is good because the instrument is easily operated and transported by a single person. For assessment of the new instrument, the time needed to make measurements compared with the duration of traditional laboratory analyses is important. Both procedures were compared with regard to the durations of field measurements, core collection and laboratory analyses.

The duration of a measurement using RhoC (determination of depth-averaged sediment composition and vertical profiles of ρ_{bulk}, ρ_{dry}, W and S) without repositioning is 30 min. Results show that a single fingerprint is sufficient to calibrate measurements on one tidal flat, whereas for the study of multiple flats multiple fingerprints are required (Eelkema 2008). De Meijer and Donaghue (1995) and Van Wijngaarden *et al.* (2002*b*) argue that three to four soil samples with varying ξ_{mu} are required to determine a representative fingerprint for a single flat. Roberti (2001) collected 20–30 soil samples to determine representative fingerprints for the Haringvliet Estuary in The Netherlands. It

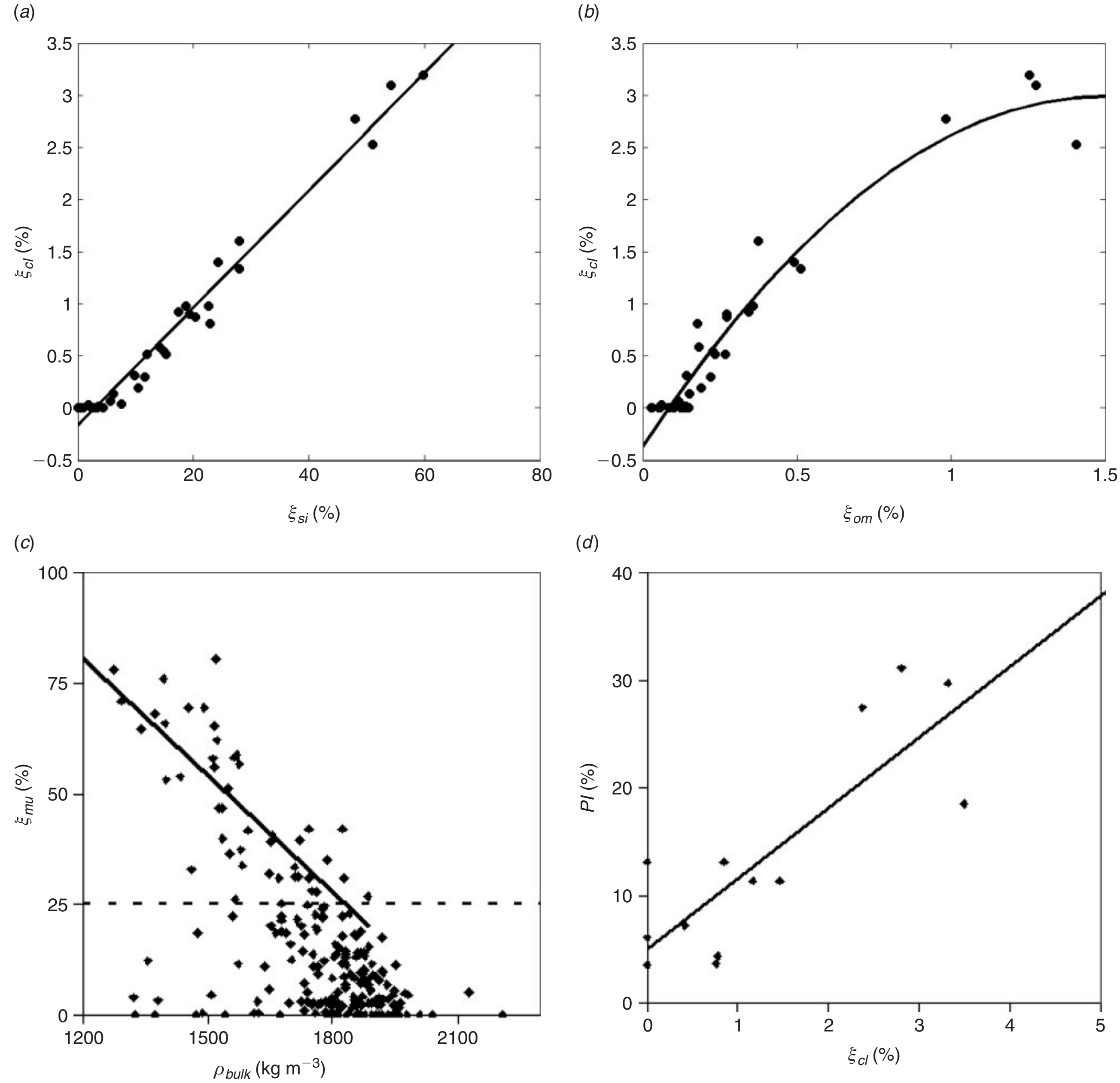

Fig. 8. Relationship between depth-averaged (*a*) silt (ξ_{si}) and clay (ξ_{cl}) contents, (*b*) mud (ξ_{cl}) and organic matter (ξ_{om}) contents, (*c*) bulk density (ρ_{bulk}) and ξ_{mu} and (*d*) the plasticity index (*PI*) and ξ_{cl}. Data were obtained by traditional laboratory analyses of the sediment cores collected in the field. The correlation coefficients (R^2) are 0.85, 0.91 and 0.62 (for $\xi_{mu} > 25\%$) and 0.89 for Fig. 8*a–d* respectively.

is concluded that 5–10 fingerprints are required to account for varying clay mineralogy on an estuary scale.

The collection of calibration cores takes ~15 min per measurement station. Subsequent laboratory analyses to obtain similar parameters to RhoC take ~4.5 h per sample. The latter takes into account the total analysis procedure of 2 months divided by 35 soil samples minus the time needed to determine vertical profiles of ξ_{om}, ξ_{cl} and ξ_{si} (the latter three parameters are not determined by RhoC). Formulations describing the duration of the traditional (T_{trad} (h)) and Medusa RhoC (T_{RhoC} (h)) measurement procedures yield:

$$T_{trad} = (0.25 + 4.5)x \tag{6}$$

$$T_{RhoC} = 0.5x + 3y \tag{7}$$

where x (–) is the number of measuring stations and y (–) is the number of locations (e.g. tidal flats) for which a fingerprint is required (three samples, 1 h each). A comparison of Eqns (6) and

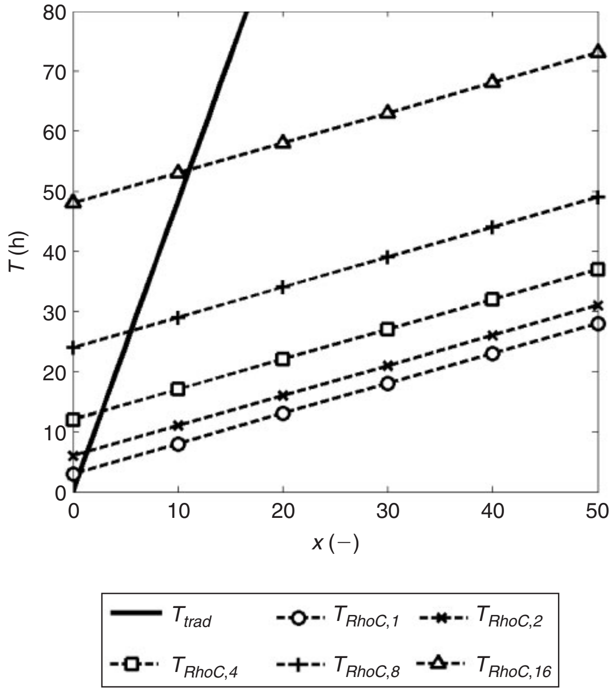

Fig. 9. Comparison of measurement durations (T (h)) for traditional methods (T_{trad} (h)) and Medusa RhoC (T_{RhoC} (h)) as a function of the number of measuring stations (x (–)), based on a vertical resolution of six to eight measuring points. The numbers in the subscripts of T_{RhoC} refer to parts of a marine system for which a separate fingerprint is required (additional 3 h for each fingerprint).

(7) in Fig. 9 shows that on an estuary scale (8–16 fingerprints), the new instrument is significantly more time effective for 10 or more measuring stations. For parts of marine systems (e.g. tidal flats), this number is even lower.

The availability of a large sedimentological data set enables the confirmation and validation of sedimentological relationships reported in the literature. The combination of these relationships with data obtained by Medusa RhoC (or by traditional analyses) enables the relatively simple and fast derivation of additional sedimentological parameters. Data exhibit similar relationships to those reported in the literature between ξ_{cl} and ξ_{si} (Flemming 2000), ξ_{cl} and ξ_{om} (e.g. Herman *et al.* 2001), ρ_{bulk} and ξ_{mu} (Flemming and Delafontaine 2000) and ξ_{cl} and PI (e.g. Mitchell 1976). The scatter of the latter relationship is attributed to the little-studied and sometimes contradicting effect (Odell *et al.* 1960; Malkawi *et al.* 1999) of ξ_{om} on PI. The negative relationship between ξ_{mu} and ρ_{bulk} follows from an increasing volume fraction of mud with increasing ξ_{mu} and, owing to the water-binding capacity of mud, larger W and lower ρ_{bulk}.

The specific ratios of the four relationships depend on the cohesive properties of the clay fraction and, therefore, on the existing clay mineralogy. These specific ratios are highly sensitive to the method used to determine the grain size distribution. Variations of up to 100% exist for ξ_{cl} when using different methods of analysis (Jacobs *et al.* 2007*b*). The existence of these relationships significantly increases the number of parameters that can be derived from the RhoC data and saves a significant amount of time because the analyses (plus core collection) used to obtain these additional parameters require an extra 2–3 h per soil sample. These additional data are particularly useful for the study of biological activity and the mechanical behaviour of intertidal sediment beds, which relate to ξ_{om} (e.g. Widdows and Brinsley 2002) and PI (e.g. Schofield and Wroth 1968) respectively.

Conclusions

The new Medusa RhoC instrument combines an existing technique to determine depth-averaged sediment composition with a new technique to measure vertical ρ_{bulk} profiles for depths ranging between 2.5 and 20 cm. The instrument was calibrated and its applicability with regard to field usage and the duration of the measurement procedure was assessed. The depth-averaged sediment composition was well represented for intertidal sediment beds. For individual tidal flats, a single fingerprint is sufficient. Varying calibration fingerprints are required to determine system-wide data for sediment composition because the clay mineralogy within marine systems may vary slightly.

Vertical ρ_{bulk} profiles show a structural overestimation as well as an oscillating character compared with the profiles determined by traditional laboratory analyses of sediment cores. The cause of the offset is not yet fully understood, although a relationship exists with the saturation degree. Correcting the results using this relationship and a smoothing procedure generates a good correlation between the ρ_{bulk} profiles of the RhoC and sediment cores. Oscillations result from random measurement errors and from the applied algorithm to determine vertical ρ_{bulk} profiles. An alternative method using multiple ρ_{bulk} at constant z is proposed because this results in smoother ρ_{bulk} profiles and a better agreement with the profiles obtained in the laboratory.

In conclusion, the Medusa RhoC instrument is a useful and practical tool to map sediment properties, and it is significantly faster and more cost effective than traditional methods. Furthermore, the combination of four confirmed sedimentological relationships with data obtained by RhoC further enhances the applicability of this new instrument, for example, to study biological or morphological processes within the bed.

Recommendations

First, the offset in the density measurements in relation to the saturation degree should be further analysed, for example, by considering the effect of partly saturated (natural) mud in controlled laboratory conditions. It is also recommended that possibilities to measure ρ_{bulk} in the upper 2.5 cm of the sediment bed be examined because this is the most active layer with regard to morphological and biological processes. Furthermore, the accuracy of data following from the application of the sedimentological relationships to the measurement data of Medusa RhoC can be improved by coupling the depth-averaged sediment composition to the vertical density profiles. The latter can provide information on the specific thickness of the upper layer of the sediment bed from which natural activity is recorded by the detector. Finally, the TDR sensor should be fixed and its working should be verified for field conditions.

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