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A novel approach to discriminate sedimentary characteristics of deltaic tidal flats with terrestrial laser scanner: Results from a case study

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ABSTRACT

Sediments in deltaic tidal flats regulate physical and chemical processes. Grain-size distribution plays an important role in determining sediment dynamics and substrate properties. However, it is challenging to quantify large-scale depositional environments in intertidal flats, due to time-consuming grain-size analyses and sparse sedimentary information extracted from scattered sediment samples. In this study, a novel terrestrial laser scanner (TLS) based method was developed to characterize the substrate of an intertidal flat. Surface sediment samples in the Nanhui flats in the Yangtze Delta, China, and the corresponding waveform amplitudes of TLS echoes at fixed sampling sites were collected for a total of 22 months. A negative logarithmic relationship was found between the sediment sand fraction, average grain size, D_{50}, and corrected waveform amplitude of TLS echo in different hydro-meteorological conditions. The mean of average grain size of five sediment sampling sites along a transect was 58.78 μm when measured by traditional grain-size analysis, and 49.48 μm when calculated with the proposed logarithmic equation. The mean error at each site was up to 21.77%. The mean error for the sand and silt fraction at each location was as high as 27.28% and 21.75%, respectively. The spatial distribution pattern of TLS-based average grain size in the entire study area was consistent with the measured pattern with a Root Mean Square Error of 13.83 μm. These errors could be caused by the accuracy of the TLS waveform amplitude correction and by limits of the method in recognizing different substrates. The effects produced by the presence of microphytobenthos (for example, cyanobacterial mats or diatom biofilms) or bedforms have not been investigated and may have affected the results. The TLS-based grain-size measurements can rapidly and effectively discriminate sediment characteristics, thus avoiding traditional time-consuming measurements. It is expected that the TLS-based method proposed here will have wide applications in shoreline studies, especially in inaccessible tidal flats.

Keywords Grain-size distribution, inversion, sediments, terrestrial laser scanner, tidal flats.

INTRODUCTION

Deltaic tidal flats develop seaward due to the accumulation of fine-grained sediments discharged by large rivers. Because of their location at the interface between land and ocean, these landforms are subject to the interaction of complex and variable terrestrial and marine processes (Short, 1991; Kane *et al.*, 2008; Kane & Pontén, 2012; Coco *et al.*, 2013). Land reclamation and sea-level rise driven by global warming are threatening these important environments. As a result, the long-term geomorphological evolution of deltaic tidal flats has attracted the attention of many researchers in recent years (Donnelly & Bertness, 2001; Jiang *et al.*, 2005; FitzGerald *et al.*, 2008; Fagherazzi *et al.*, 2012). The substrate of tidal flats is a mixture of siliciclastic sediment (clay, silt and sand) and organic material deposited by vegetation and benthic organisms (Friedrichs, 2001; Maan *et al.*, 2015). Sediment grain-size distributions and related sedimentary structures are crucial physical–ecological indicators of intertidal flat environments; for example, intertidal biological communities vary significantly in muddy or sandy environments (Evans, 1965; Herman *et al.*, 2001). Concentrations of alkali, metals and nutrients also change with grain size in intertidal sediments (Zhang *et al.*, 2002), algae survival and vegetation growths (for example, seagrass and salt marshes) are also affected by the characteristics of the substrate (Bos *et al.*, 2007; Park & Hwang, 2011). In addition, local sediment dynamics are closely related to grain size on muddy tidal flats (Law *et al.*, 2013). Tidal flats typically form in locations subject to enhanced siltation; the encroachment of vegetation further supports accretion due to accumulation of organic matter (Swales *et al.*, 2004; Beck *et al.*, 2008; van Leeuwen *et al.*, 2010). Therefore, revealing the temporal and spatial characteristics of surface sediments in tidal flats, and changes in grain-size distribution can help in understanding sediment transport, morphological evolution and ecological processes taking place in the substrate.

Typically, sediment characteristics can be derived from traditional grain-size analyses of field samples. Several decades ago, sieving was used for non-cohesive sediments (Konert & Vandenberghe, 1997; Munroe & McKinley, 2007), while the diameter of fine sediments was derived from Stokes sedimentation rates in a settling column. The conversion of settling velocity to particle diameter required precise measurements (Komar & Cui, 1984; Flemming, 2007). Sieving and settling columns are time-consuming methods that need a large number of sediment samples.

In recent decades, optical methods have been developed to determine sediment grain size based on the diffraction (or scattering) of a monochromatic laser light (Swithenbank *et al.*, 1976; Gartner *et al.*, 2001). These methods are fast and precise, but are limited by the grain sizes of the collected sediment samples and often underestimate the fine fraction (Beuselinck *et al.*, 1998; Murray, 2002). The laser method is a time-saving and effortless technique, which allows processing of large numbers of samples.

Recently, dynamic image analysis, based on numerous two-dimensional projected images, was introduced to measure grain-size distributions and determine grain shape (Tysmans *et al.*, 2006; Sun *et al.*, 2019). The four methods presented above are mainly conducted in the laboratory, and have been used with success to analyze samples collected in rivers, estuaries and along shorelines.

In some settings, the collection of bottom sediments can be challenging or dangerous due to soft muddy substrates, inaccessible tidal creeks or protected areas. This is especially true when sedimentary characteristics need to be studied across a large area. Moreover, a gradually varying topography can present subtle differences in local sedimentary environments; in these cases, methods based on few sediment samples cannot reflect the large-scale depositional variations of a tidal flat. It is therefore necessary to develop new methods that can dynamically detect large-scale sedimentary characteristics and their variations in a tidal flat. These methods can be of help in the protection and restoration of sedimentary environments and related ecosystems.

Remote sensing provides new tools for the analysis of surface sediments. Spectral mixture models were used on Landsat 5 images to map the intertidal sediment distribution in the Wash, England (Yates *et al.*, 1993). An Airborne Thematic Mapper was also applied to detect the intertidal sediment distribution in the Ribble Estuary, UK (Rainey *et al.*, 2003). This remote sensing technique was less accurate in sandy environments than in muddy ones. The effectiveness of measuring surface grain size of riverine bedforms with airborne images at a resolution of centimetres has been also assessed (Carbonneau *et al.*, 2004). Although aerial images can provide sediment characteristics with a fine spatial scale, they are costly and only detect the distribution of the median grain size; methods detecting different sediment fractions are not available. The relationships among back-scattering, mud content, median grain size, roughness and sediment texture were determined from SAR (synthetic-aperture radar) imagery by van Der Wal *et al.* (2005) in an intertidal surface in The Netherlands. Multi-frequency radar data were also applied for the classification of tidal flat sediments (Gade *et al.*, 2008). Although radar-based detection is not affected by weather conditions, its lower resolution is insufficient to study fine sedimentary characteristics of tidal flats. Hence, unmanned aerial systems, a multispectral camera and four multispectral sensors (covering red, green, red edge and near-infrared bands) were used to explore moisture content and median grain size in three intertidal flats, demonstrating the linkage between sediment composition and spectral characteristics (Fairley *et al.*, 2018). The study of intertidal sediments and related geomorphic processes using remote sensing has received attention in recent years (Choi *et al.*, 2010, 2011; Tseng *et al.*, 2017; Kim *et al.*, 2019; Park, 2019). However, remote sensing inversion of sediment characteristics is often limited by spatial resolution, atmospheric disturbance and high cost.

To determine the evolution of intertidal landforms, it is crucial to understand the spatiotemporal characteristics of intertidal sedimentary environments at the centimetre scale and their micro-geomorphic processes. To this end, it is urgent to develop a detection technology that is accurate, efficient and less labour intensive.

With the development of active and long-range remote sensing technology, laser scanners based on LiDAR (light detection and ranging) have become common. These methods include both terrestrial laser scanning (TLS) and airborne LiDAR scanning (ALS; Tang *et al.*, 2014; Kashani *et al.*, 2015). TLS rapidly emits anti-interference monochromatic laser beams in succession and obtains high-precision, high-density three-dimensional panoramic information about objects, with the advantages of being contactless and low risk (Bitelli *et al.*, 2004; Hartzell *et al.*, 2014). Here, a TLS (Riegl VZ-4000; Riegl, Horn, Austria) was used to acquire intertidal point data. The instrument provides excellent long-distance measurement capability (up to 4000 m), with unique echo digitization and online waveform processing functions. Therefore, it can acquire long-distance 3D coordinates of intertidal landforms with high resolution and echo information at full waveform. The LiDAR scanner can overcome the deficiencies of traditional field measurements in complex terrain, providing data with high spatial resolution (Tang *et al.*, 2015).

Terrestrial laser scanning (TLS) has been widely applied to determine morphological change, vegetation biomass and biomorphodynamic attributes in coastal and intertidal areas, due to its precision and high spatial resolution (Guarnieri *et al.*, 2009; Owers *et al.*, 2018). Airborne hyperspectral images and TLS data were used to analyze the mineralogical attributes of coastal dunes. Manzo *et al.* (2015) pointed out that grain size and mineral composition lead to essential differences in the TLS echo. Seasonal trends in the foredune ridges along the North Adriatic Sea coast (Italy) were detected using TLS-derived digital elevation models (Fabbri *et al.*, 2017).

The combination of satellite imagery and TLS data has only recently received attention in the study of fluvial and intertidal sediments. TLS could provide analytical information on the threshold for sediment resuspension of bottom sediments (Neverman *et al.*, 2019). Bottom echo residuals from airborne full-waveform bathymetry were isolated, and used to classify sandy and rocky seafloor sediments (Eren *et al.*, 2018). Grain-size distributions of river sandbars were estimated accurately using airborne topographic LiDAR in the Rhine River, and compared to distributions derived from 'photosieving' (Chardon *et al.*, 2020).

Therefore, the TLS technology can provide grain-size distribution and variations of surface sediments in tidal flats at a very high spatial and temporal resolution. Traditional studies are mostly based on a limited number of sediment samples, and therefore require interpolation to obtain spatial distributions of grain parameters (Wang & Ke, 1997; Yoo *et al.*, 2007; Law *et al.*, 2013). Moreover, historical changes in sediment characteristics were often obtained from sediment cores and sedimentation profiles at low spatial resolution (Baumfalk, 1979; Ghinassi, 2007; Yamashita *et al.*, 2009; Watson *et al.*, 2013; Ghinassi *et al.*, 2018a). To determine the temporal evolution of bottom sediments, multi-spectral images can also be used, but this method is limited by the coarse spatial resolution of the images and the low revisit period (van Der Wal *et al.*, 2005; Fairley *et al.*, 2018).

For small-scale areas, the high accuracy and resolution of TLS is ideal for discrimination of sedimentary characteristics. Preliminary studies with this novel method have focused on sediment classification using the physical shape of the grains (Deronde *et al.*, 2008; Diaz-Gomez *et al.*, 2019; Engin & Maerz, 2019; Conesa-García *et al.*, 2020). Burns & Lück-Vogel (2017) explored the relationship between sediment grain size and TLS echo intensity in the laboratory, but they did not apply the method to mixed fractions in the field.

Few studies have focused on the use of high-precision TLS to detect sediment grain sizes and their variations in tidal flat environments. Since the TLS echo information of different sediments is different, the utilization of TLS to reveal grain-size characteristics of deltaic tidal flats is theoretically possible. The present study uses TLS to determine the sedimentary characteristics in a specific study area (140 m × 80 m) of the Nanhui tidal flat, which is representative of the tidal flats in the Yangtze Delta, China (Dai *et al.*, 2015; Fig. 1A to C; Text S1). The Nanhui tidal flat is located in the southern margin of the Yangtze Delta. This open geomorphic system is dominated by strong runoff, high tidal energy and wave power, and the surface sediments are coarse-grained. The results are compared with surface sediment samples collected in different months. The main objectives of the paper are: (i) to quantify the relationship between TLS echo information and sediment grain size; (ii) to improve the TLS-based method for sediment inversion in tidal flats; and (iii) to determine the factors affecting TLS-based results, and in particular the effect of intertidal slopes. Our results introduce a new technique for diagnosing depositional environment in large-scale tidal flats around the world.

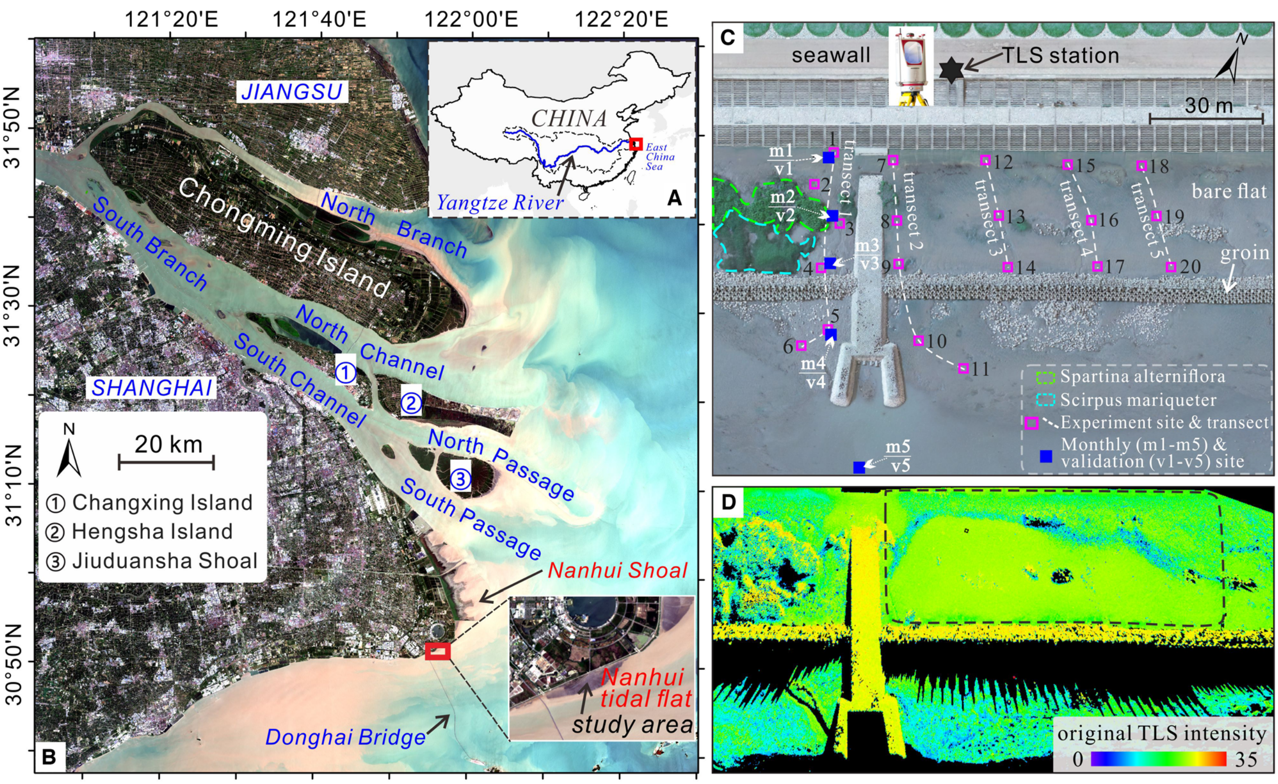

Fig. 1. Study area. (A) Location of the Yangtze River in Asia. (B) Three-order bifurcated distributaries of the Yangtze Estuary. The Nanhui tidal flat studied here is located on the southern marginal tidal flat shown in the red rectangle. Artificial reclamation projects (blue dashed curve) and Donghai Bridge near the Nanhui tidal flat are also indicated. (C) Observation station of the Terrestrial Laser Scanner (TLS; Riegl VZ-4000) on the seawall, and the distribution of surface sediment sampling sites. The 20 magenta hollow squares and five white dotted lines indicate the transects of the experimental sampling sites, and five blue solid squares (m1/v1 to m5/v5) indicate the monthly and validation sampling sites (Table 1). (D) Original intensity of TLS echo, a rectangular area was set to study the relationship between sediment grain size calculated with TLS echo and measured in the laboratory.

DATA ACQUISITION AND METHODS

Nanhui tidal flat

The Nanhui tidal flat is located in the Nanhui Shoal which lies in the southern margin of the Yangtze Delta, China. The Nanhui Shoal is adjacent to the South Passage and is the fastest growing area in the delta, benefitting from previous abundant sediments transported into the subaqueous delta (Dai *et al.*, 2015; Fan *et al.*, 2017; Wang *et al.*, 2020; Fig. 1B). Around the Nanhui Shoal the tide forcing is semi-diurnal with an average tidal range of 2.7 m, and the mean tidal level in winter is lower than in summer (Wang *et al.*, 2018; Wei *et al.*, 2020). The main direction of tidal currents in the Nanhui tidal flat is parallel to the local shoreline, and the dominant flood tidal current is directed south-east. The seasonal north-east waves also affect intertidal sedimentary dynamics (Fu *et al.*, 2007; Fan *et al.*, 2017). Over the past two decades, reclamation projects and the construction of the Donghai Bridge and seawalls have modified the nearshore hydrodynamics in the Nanhui Shoal (Fig. 1B).

The length and width of the entire study area are 140 m and 80 m, respectively. The locations of sediment sampling and TLS observations were located seaward of a reclamation seawall near a breakwater (Fig. 1C). Sporadic patches of salt marsh vegetation (*Spartina alterniflora* and *Scirpus mariqueter*) grow on the east side with a canopy height less than 0.5 m; the intertidal elevation decreases seaward. Tidal forcing and wave power in the Nanhui tidal flat are strong, and the area experienced erosion after the construction of the artificial structures (Wang *et al.*, 2018); as a result, sediments coarsened and it is now mainly sand and silty sand.

Multi-period sediment samplings

Surface sediments were regularly collected at fixed sites in the Nanhui tidal flat from January 2017 to July 2019 (Table 1; Fig. 1B and C). The substrate was sampled in 5 cm squares with a thickness that does not exceed 0.5 cm, to minimize impact and ensure the uniformity of collected sediment properties. Each sediment sample was carefully collected using a thin hard plastic sheet and immediately stored in a sealed and numbered plastic bag. Three different sets of sediment data were collected:

1 *Experimental sites*: a total of 20 sediment sampling sites were arranged along five transects on 22 June 2019, and numbered from s01 to s20 (Table 1; Fig. 1C). The transects spanned different sedimentary substrates, and can therefore reveal potential correlation between sediments and corresponding waveform features of TLS echo. Figure 1C shows transect 1 to transect 5 from west to east – all sampling sites were distributed on a bare flat with good accessibility. Only sediment samples s5, s6, s10 and s11 were located on the outside of the breakwater where the bottom is muddy, the other samples were collected between the seawall and the breakwater, where the bottom sediments are coarse. During the collection and observation period, some visible markers (bottles or bamboo poles) were erected behind each sampling site to mark the position and then to extract the corresponding TLS data.

2 *Monthly sampling sites*: samples were taken every month at five fixed intertidal sites (m1 to m5), during the period January 2017 to July 2019 (Table 1; Fig. 1C). The position of these five sampling sites was stable relative to the adjacent seawall, breakwaters and vegetation edges. Each monthly sampling was carried out with the same approach of the above experiment. Due to

Table 1. Dates of sediment sampling and terrestrial laser scanner (TLS) observation of different data sets.

Data set	Date
Experiment	22 Jun. 2019
Monthly	04 Jan. 2017; 14 Apr. 2017; 22 Aug. 2017; 24 Oct. 2017 19 Jan. 2018; 16 Apr. 2018; 20 Jul. 2018; 10 Oct. 2018; 01 Dec. 2018 23 Jan. 2019; 23 Mar. 2019; 23 Jun. 2019; 22 Jul. 2019
Validation	
Winter	02 Dec. 2016; 13 Feb. 2017; 05 Feb. 2018; 23 Feb. 2019
Summer	13 May. 2017; 29 Jun. 2018; 20 Aug. 2018; 18 Jul. 2019

alongshore sediment transport and the sheltering effect of the breakwater, sites m4 and m5 are muddy, while the other three sites have a coarse grain size. Only surface sediments were collected each time. The monthly sediment data were used to explore links between grain parameters and TLS echo on a long timescale. The two sets of data were combined in the final analysis.

3 *Samples for validation*: additional sediment data collected in eight months (four in winter and four in summer), were utilized to determine the reliability of the results. The five locations of the validation data (numbered from v1 to v5) were identical to the monthly sampling for consistency, but the sampling dates were different (Table 1; Fig. 1C). Since the tidal forcing in the Nanhui tidal flat is strong, during high tide the currents erased all substrate disturbances caused by sediment sampling.

Collection of TLS data

Both 3D coordinates and echo information of point cloud data are acquired by full-waveform TLS, including intensity angle of echoes and waveform characteristics (Hakala *et al.*, 2012). Echo intensity is the backscattered laser signal returned by a reflected object. The signal is recorded as a dimensionless digit; the full-waveform TLS (Riegl VZ-4000) obtains the complete waveform of one echo pulse after reflection from a specific object (Kashani *et al.*, 2015). The echo waveform is affected by the different physical attributes of an object, and many researchers have used this information to classify objects (Bitelli *et al.*, 2004; Brodu & Lague, 2012; Koenig *et al.*, 2015).

During the observation periods, the TLS (Riegl VZ-4000) was fixed on a tripod and placed on the seawall (the black hexagon in Fig. 1C), the working principles of TLS are illustrated in Text S2. Each observation was conducted during the lowest ebb tide, to ensure the least water accumulation in the intertidal flat and thus dry conditions. Measurements were carried out during fair weather to reduce atmospheric disturbances. The vertical and horizontal resolutions of the Riegl VZ-4000 were set to approximatively 0.004° and 0.03°, and the laser pulse frequency remained the same at 150 kHz. From January 2017 to July 2019, a total of 22 TLS datasets were collected (Table 1). The TLS observations were divided into three groups: (i) Experimental observations: point cloud data on 22 June 2019 were used to relate TLS echo waveform (amplitude and width) to sampled sediments; the same data were also used to describe the relationship between echo intensity and waveform amplitude. (ii) Monthly observations: TLS coordinates and echo intensity of intertidal sediments were obtained in 13 monthly observations. The echo intensities were converted into waveform amplitudes based on the above experimental sites, and the relationship between waveform amplitudes and main sediment grain-size parameters analyzed. (iii) Observations used for validation: TLS data collected in eight months, four in winter and four in summer, were used to verify whether the derived relationships are reliable.

Measurements of grain size in surface sediments

Sediment samples were pre-treated as shown in Text S3. Dynamic image analysis of Camsizer XT (Retsch Technology, Haan, Germany) was used to obtain the percentage of different grain-size fractions for all sediment samples. The moment method formulas (McManus, 1988) were used to calculate sediment grain-size parameters (average grain size, sorting factor, skewness and kurtosis in Text S4, Fig. 2):

$$X_{\text{average}} = \sum_{i=1}^{n} X_i * f_i/100 \tag{1}$$

$$\delta = \sqrt{\sum_{i=1}^{n} (X_i - X_{\text{average}})^2 * f_i/100} \tag{2}$$

$$\text{Sk} = \sqrt[3]{\sum_{i=1}^{n} (X_i - X_{\text{average}})^3 * f_i/100} \tag{3}$$

$$\text{Ku} = \sqrt[4]{\sum_{i=1}^{n} (X_i - X_{\text{average}})^4 * f_i/100} \tag{4}$$

where X_i is the median value of a grain-size class, f_i is the percentage of this grain-size class, X_{average} is average grain size, δ is sorting factor, and Sk and Ku are skewness and kurtosis of the distribution frequency curve of different grain-size classes. The percentage of different grain sizes can be obtained from the measured grain-size parameters. The median grain size (D_{50}) was also calculated as the grain size corresponding to 50% of the frequency cumulative curve. Clay (0.5–4.0 μm), silt (4.0–62.5 μm) and sand (62.5–500 μm) fractions were quantified based on sediment classification standards developed by the American Geophysical Union. The sediments in intertidal flats were also classified according to the Shepard nomenclature (Folk & Ward, 1957). Water content was measured in the

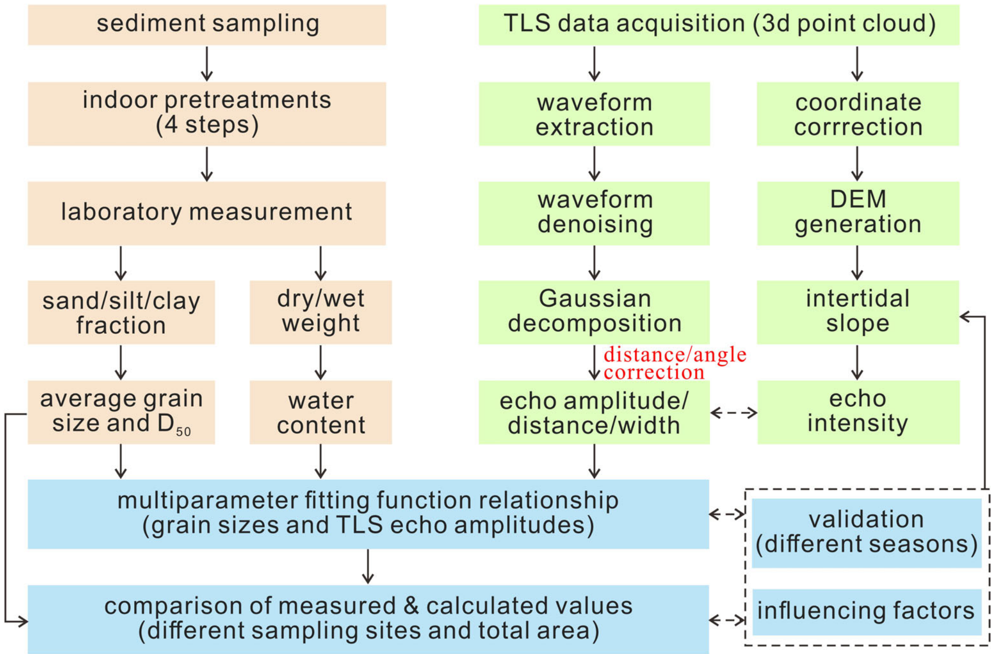

Fig. 2. Flow charts for data processing and analysis. Mainly data processing includes three parts: sediment grain-size measurements, corrections of waveform amplitude of terrestrial laser scanner (TLS) echoes and multi-parameter function relationship determinations. Finally, the charts discuss the verifications of those constructed relationships and analyze the potential influencing factors.

sediment samples collected on 22 June 2019 in the Nanhui tidal flat (Text S4). First each sediment sample was weighed three times with a high-precision electronic balance and the average value was taken as the final wet weight (W_{wet}). Then all samples were put into an oven at 65°C for 48 h, and they were weighed again to get dry weight (W_{dry}). Water content in 20 sediment samples (SWC) can be calculated with the following formula:

$$\mathrm{SWC} = \left[(W_{\mathrm{wet}} - W_{\mathrm{dry}})/W_{\mathrm{wet}}\right] \times 100\% \qquad (5)$$

Waveform decompositions and TLS amplitudes

Echo intensities (waveform amplitudes) are affected by multiple factors: distance, incidence angle, reflectivity and atmospheric attenuation (Yoon *et al.*, 2008). Therefore, original echo information needs to be corrected before detecting the properties of different sediments. In the current normalized model of echo correction transmission, distance and other parameters are averaged (Höfle & Pfeifer, 2007). In this study, the TLS echo waveform of each sediment sample was processed in the following four steps to obtain amplitude and width.

First, the location of sampled sediments was extracted from the TLS point cloud. Points within an area of 10 × 10 cm from the collected sediment sample were extracted, and their echo intensity and waveform features analyzed. Coordinates of each point cloud were converted from internal instrument coordinates to World Geodetic System (WGS1984) and the Wusong Datum (reference to theoretical lowest tidal level in the Yangtze Delta; Figs 1D and 2). Second, signal noise was removed from each waveform (Text S5), based on a threshold value. The threshold was determined using the standard deviation of waveform noise (σ_{noise}) after calculating the median absolute deviation, using the formulas (Persson *et al.*, 2005):

$$\sigma_{\mathrm{noise}} = \alpha * \mathrm{median}\left(\left| f_i(t) - m\right|\right) \qquad (6)$$

$$m = \mathrm{median}\left(f_i(t)\right) \qquad (7)$$

where σ_{noise} is waveform noise, α is 1.4826 (consistency factor for a distribution similar to a normal distribution), $f_i(t)$ is original waveform amplitude. After calculating waveform noise, it was subtracted from the original waveform. Third, the waveform was decomposed. The emitted laser pulse signal and echo signal are similar to Gaussian distributions, so that waveform data are superimposed by a series of Gaussian scattering signals. Therefore, a Gaussian model can be used to describe echo waveform of the surface sediments (Chauve *et al.*, 2008; Text S5).

$$y = \sum_{i=1}^{n} A_i * \exp\left[-\frac{(x-\mu_i)^2}{2\sigma_i^2}\right] + b \tag{8}$$

where A_i is amplitude of the i Gaussian component, μ_i is the position of the peak of the i Gaussian component (distance), σ_i is standard deviation (width), n is the number of Gaussian components and b is the background noise. From the model amplitudes, widths and distances of echo waveforms corresponding to all sediment samples can be obtained. Fourth, distance and angle were corrected. Waveform amplitudes after the above decomposition are related to distance and laser incidence angle, so the amplitude needs to be corrected. The original TLS echo intensity decreases linearly with increasing distance from TLS (Fig. S1); therefore, this linear correction method (attenuation process) was used to achieve distance correction for all echo amplitudes, and reference distance (60 m) is the mean between all sediment sampling sites and TLS. The method of incident angle correction is similar to distance correction: the distance is assumed to be constant, the corrected echo amplitudes are inversely proportional to the cosine of the incident angle, the $\cos\theta_{\mathrm{ref}}$ is zero (Text S6, Fig. 2).

$$A_{c\_\mathrm{diatance}} = A * (D/D_{\mathrm{ref}}) \tag{9}$$

$$A_{c\_\mathrm{diatance\_angle}} = A_{c\_\mathrm{diatance}} * (\cos\theta_{\mathrm{ref}}/\cos\theta) \tag{10}$$

In addition, intertidal slope in different observation months was also calculated, to analyze the seasonal relationships between slope and corresponding fitting parameters and correlations. Substrate slope is defined in Eqs 11 and 12 for the monthly observation sites m1 and m5:

$$\mathrm{Slope} = \sin^{-1}|(Z_{m1} - Z_{m5})/D| \tag{11}$$

$$D = \sqrt[2]{(X_{m1} - X_{m5})^2 + (Y_{m1} - Y_{m5})^2 + (Z_{m1} - Z_{m5})^2} \tag{12}$$

where (X_{m1}, Y_{m1}, Z_{m1}) and (X_{m5}, Y_{m5}, Z_{m5}) are the 3D coordinates of sites m1 and m5, respectively (Text S7).

In this study, echo waveform features were obtained only during the experimental observations, and then used to convert corrected echo intensities observed every month to waveform amplitudes of TLS echoes. The experimental data of the two corrections were extracted to clarify the mutual relationships. The results show a very significant linear increasing trend with correlation coefficient of 0.99 (Fig. S2):

$$\mathrm{Intensity}_c = 0.012 * \mathrm{Amplitude}_c - 0.028 \tag{13}$$

$$\mathrm{Amplitude}_c = 82.228 * \mathrm{Intensity}_c + 14.390 \tag{14}$$

where $\mathrm{Intensity}_c$ and $\mathrm{Amplitude}_c$ are the corrected echo intensity and waveform amplitude, respectively.

After analyzing the variations in sediment grain-size parameters and TLS echo amplitude characteristics of the Nanhui tidal flat, the relationship between the two datasets was proposed. The sediment average grain sizes in the study area in January 2019 were then calculated from the TLS echo information, to determine consistency between the measured and TLS-based calculated results. In addition, the average grain size in June 2019 was calculated to compare the spatial patterns and seasonal variation in sediment characteristics.

RESULTS

Grain-size distributions

Grain-size distributions of surface sediments in the Nanhui tidal flat measured by the Camsizer XT show the presence of spatial gradients. Along the first transect (site s01–s06), the distribution gradually changes from bimodal to unimodal moving offshore, with sand fraction declining (Fig. 3A), and average grain size decreasing from 98.28 to 29.46 μm (Table 2). Water fraction of the sediments increased seaward from 20.05 to 33.40% as the grain size becomes smaller (Table 3). Grain-size variations were similar along the other transects (transects s07–s11, s12–s14, s15–s17 and s18–s20; Fig. 3B to D). Results indicate that overall sediments were coarser with lower water content near the seawall due to wave breaking and absence of marsh vegetation, while sediments were fine in the lower seaward tidal flat with uniform water content (between 17.89% and 27.13%; Tables 2 and 3). Sediments were also finer along the

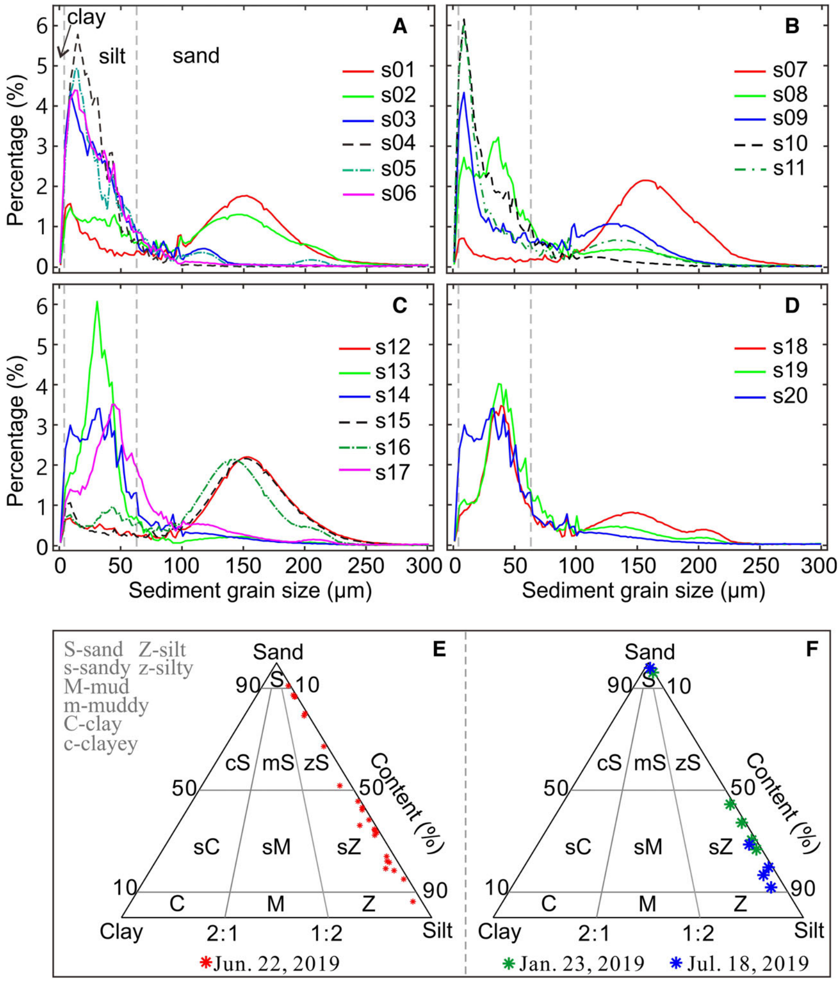

Fig. 3. Frequency distribution of sediment grain size (0–300 μm) of the 20 experimental samples collected on 22 June 2019, the clay fraction of all sediments was low. (A) site: s01–s06; (B) site: s07–s11; (C) site: s12–s17; and (D) site: s18–s20. (E) Folk's triangle classification of experimental sediments; and (F) nomenclature of sediments collected on 23 January 2019 (winter, green asterisks) and on 19 July 2019 (summer, blue asterisks), respectively.

western side, consistent with a higher elevation and the sheltering effect of the breakwater: the average grain size of transect 18–20 was only 66.54% of transect 7–8 (Table 2).

According to Folk's triangle classification, the substrate is sand at sampling site s01 (sand fraction 91.01%) and silt at site s04, with a clay fraction of 6.3% (Fig. 3E). Six of the remaining sites were classified as silty sand and twelve as sandy silt, (Figs 1C and 3E). Coarse sediments were located near site s07, while shoreward and near the breakwater the sediments were fine (Table 2). The silt fraction increased in summer (July 2019) with respect to winter (January 2019; Fig. 3F).

Waveform amplitude of TLS echoes

Elevation was higher near the seawall and gradually decreased seaward, with the elevation difference along each transect between 0.53 m and 0.89 m (Fig. 4A). The original waveform amplitudes after the Gaussian decomposition were between 1300 and 1800, except for the lower values of 838 and 1235 at sites s11 and s12, respectively. Overall and along each transect the original amplitude is not related to elevation and grain size (Fig. 4A). After distance and angle corrections, the waveform amplitudes displayed an increasing trend moving offshore, except for sites s06 and s11 (Fig. 4A). The percentage difference between the maximum and minimum amplitude for each transect was 129.79%, 175.76%, 162.74%, 60.58% and 52.10%, respectively. In addition, the elevations of the five sediment sampling sites along each transect were inversely related to the waveform amplitudes after correction (Fig. 4A). These results indicate that the lower the elevation, the finer the sediments, and the greater the corrected waveform amplitude of TLS echo (Fig. 4A).

Table 2. Grain-size parameters of intertidal surface sediments.

Site	Sand fraction (%)	Silt fraction (%)	Clay fraction (%)	Average grain size (μm)	D_{50} (μm)	δ	*Sk*	*Ku*
s01	79.26	19.25	1.49	98.28	140.56	1.55	1.77	2.34
s02	67.22	31.63	1.15	79.52	119.81	1.48	1.57	2.15
s03	22.14	74.55	3.31	31.61	31.32	1.69	0.58	2.33
s04	6.30	90.82	2.88	21.73	23.24	1.17	0.65	1.74
s05	21.68	75.49	2.83	30.62	28.29	1.67	0.62	2.29
s06	18.48	78.64	2.88	30.45	29.46	1.67	0.69	2.38
s07	91.01	8.28	0.71	130.16	156.89	1.10	1.59	2.12
s08	32.38	65.46	2.16	41.92	41.22	1.56	0.83	2.13
s09	51.79	44.49	3.72	47.07	68.22	1.89	1.49	2.39
s10	19.25	75.56	5.19	24.99	24.57	1.73	0.55	2.33
s11	36.20	58.73	5.07	32.16	29.16	1.95	0.63	2.38
s12	86.75	12.57	0.68	119.58	150.02	1.16	1.56	2.09
s13	15.10	83.45	1.46	34.38	33.13	1.27	0.46	1.98
s14	45.67	53.43	0.91	57.13	56.28	1.35	1.11	1.93
s15	86.68	12.41	0.91	113.10	147.23	1.24	1.68	2.21
s16	80.19	19.10	0.71	70.61	100.00	1.17	1.48	1.99
s17	34.70	64.21	1.09	49.43	48.80	1.29	0.82	1.93
s18	43.25	55.99	0.76	1.34	0.92	1.90	60.07	51.31
s19	33.35	65.62	1.03	1.25	0.90	1.88	49.92	46.23
s20	24.03	73.46	2.51	1.51	0.42	2.13	35.85	37.10

Note: δ is sorting factor; *Sk* is skewness and *Ku* is kurtosis of intertidal sediment.

Table 3. Measured water content of intertidal surface sediments of the experimental set.

Site	s01	s02	s03	s04	s05	s06	s07	s08	s09	s10
SWC (%)	20.05	20.66	23.28	28.98	32.03	33.40	18.90	27.27	30.30	32.91
Site	s11	s12	s13	s14	s15	s16	s17	s18	s19	s20
SWC (%)	34.51	20.93	23.68	22.97	23.91	17.89	22.34	27.13	25.98	26.16

Note: *SWC* is the sediment water content.

The corrected echo intensities of monthly samples also vary in space (Fig. 4B). The maximum intensity differed from the minimum by 125.95%. The elevations of monthly sampling sites are the same as the transects, and the relationships between elevation, sediment grain size and corresponding waveform amplitude of TLS echoes is consistent with the experimental group (Fig. 4).

Relationship between corrected waveform amplitude of TLS echoes and grain size

The corrected waveform amplitudes of experimental TLS data varied between 650 and 2380, while that of monthly TLS data were mainly concentrated between 1030 and 2550 (Fig. 5). The sand fraction decreases when the amplitude increases, in accordance with a logarithmic fitting with a significant correlation ($\text{Sand} = -55.38*\ln(\text{Amplitude}_C) + 448.78$, $r = 0.68$ and $P < 0.05$; Fig. 5A). The 65 data points of both experimental and monthly samples were regularly distributed on both sides of the log-fit curve (Fig. 5A). The silt fraction increases with amplitude, following the equation: $\text{Silt} = 54.27*\ln(\text{Amplitude}_C) - 344.44$ ($r = 0.65$ and $P < 0.05$; Fig. 5B). The clay fraction was very low in all samples (51 sites had less than 5% clay), thus in the plot the points amplitude versus clay fraction are scattered and the logarithmic relationship between the two variables is not significant (Fig. 5C).

The average grain size was between 10 μm and 130 μm for both experimental and monthly samples; and coarser sediments had smaller standard deviation of waveform amplitudes (Fig. 6A). The amplitude and average grain size

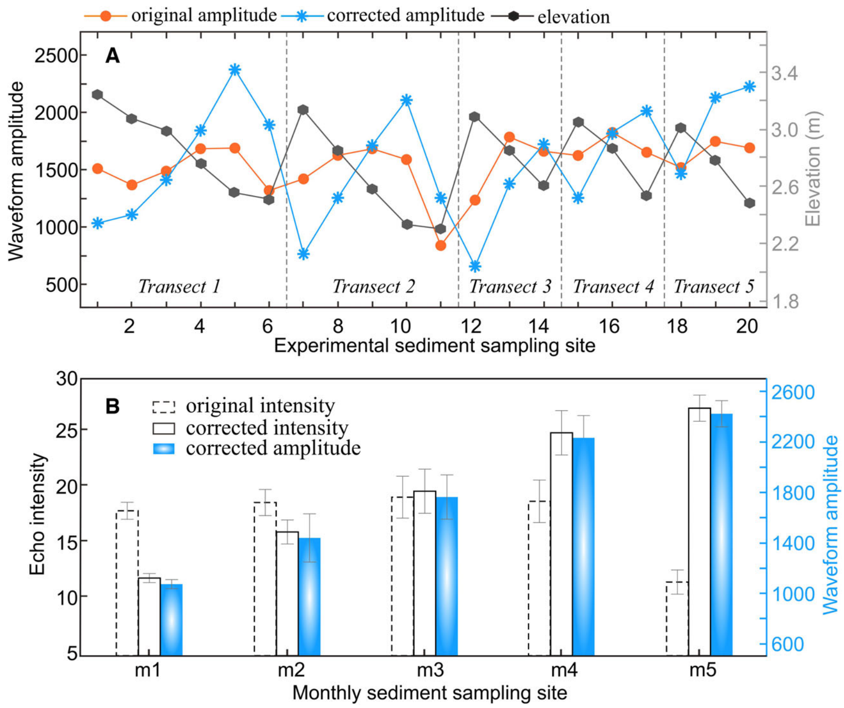

Fig. 4. (A) Original and corrected waveform amplitudes of terrestrial laser scanner (TLS) echo and corresponding elevation at each experimental sediment sampling site; five transects were set in Nanhui tidal flat and shown in Fig. 1C. (B) Original and corrected TLS echo intensity and corrected waveform amplitude of each monthly sediment sampling site.

are linked with a negative logarithmic equation ($GS_A = -67.12*\ln(\text{Amplitude}_C) + 548.96$, $r = 0.68$ and $P < 0.05$), this relationship was confirmed for both experimental and monthly samples (Fig. 6A and B). The D_{50} ranged between 130 μm and 170 μm, and also displays a negative logarithmic relationship with amplitude ($GS_D = -104.8*\ln(\text{Amplitude}_C) + 836.23$, $r = 0.67$ and $P < 0.05$; Fig. 6C). This relationship is valid for both experimental and monthly samples (Fig. 6D).

Sediment parameters inversion based on TLS method

Based on the above logarithmic relationships, three sediment fractions were calculated, average grain size and D_{50} of each experimental and monthly sediment sample to determine the difference between laboratory measurements and TLS-based values. The clay fraction in the Nanhui tidal flat is low, so it is not considered here. Overall, TLS-based calculated values are consistent with measurements, and the corresponding Root Mean Square Errors (*RMSE*) of sand fraction, silt fraction, average grain size and D_{50} are 20.09%, 19.28%, 22.68 μm and 34.56 μm, respectively (Fig. 7A and B); the Mean Absolute Deviations (*MAD*) are 16.24%, 15.87%, 17.89 μm and 28.97 μm. Mean values and standard deviations were also calculated for each monthly sample (Fig. 7E and H). The mean sand fraction derived from the log regression is 36.66% for the five monthly samples, which underestimates by 9.39% the values measured in the laboratory (40.46%, Table 4). The sampling site closest to the TLS station has the greatest relative deviation between the two values (Table 4; Fig. 7E). The mean silt fraction is overestimated by 5.01% (Table 4). The standard deviation of the measured values at the seaward sampling sites is higher than for the TLS-based values (Fig. 7F). Furthermore, the calculated mean values of average grain size and D_{50} are 7.99% and 13.32% lower than the measured ones (Table 4), the relative deviations of the middle sites are small (Fig. 7G and H).

In general, except for the clay fraction that is low and variable, the new method of estimating surface sediment characteristics from TLS waveform amplitudes is reliable. The mean of measured and TLS-based average grain size of five sediment sampling sites along a transect was 58.78 μm and 49.48 μm, respectively, indicting a difference of −7.99% (Table 4; Fig. 7). In addition, the mean of the absolute value of the error of average grain size at each site was up to 21.77%, which was relatively high (Table 4; Fig. 7). Moreover, the mean sand and silt fractions at all sampling sites have lower errors of

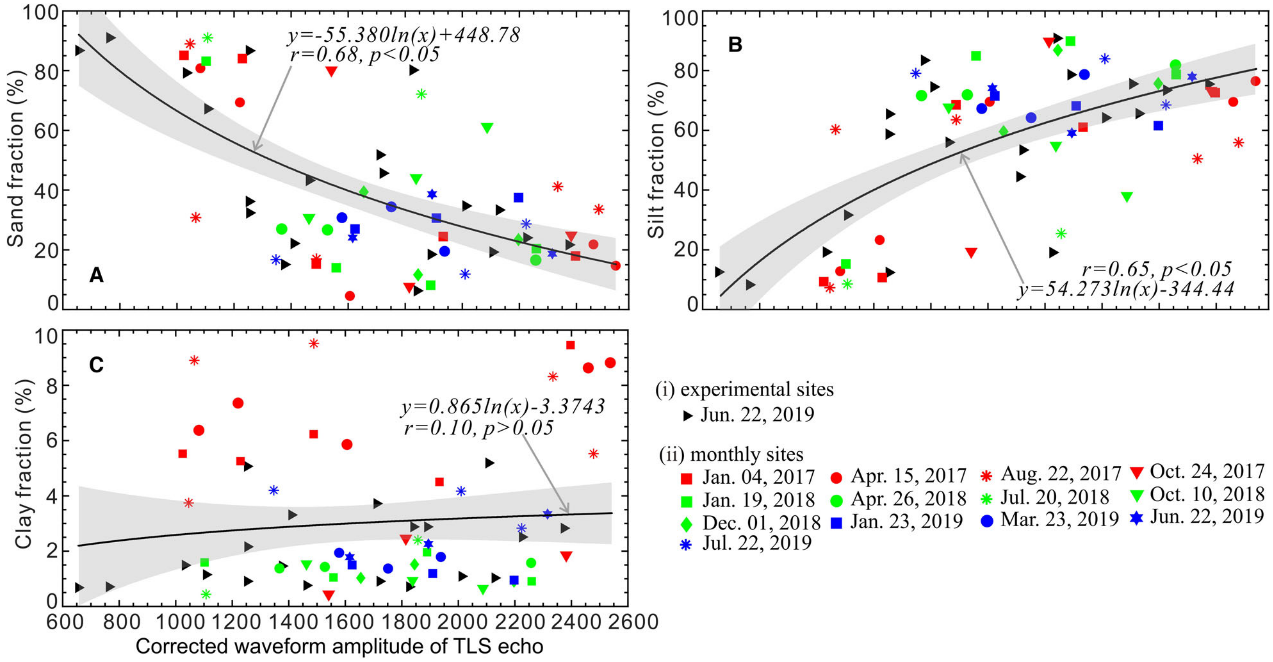

Fig. 5. Relationships between the corrected waveform amplitudes of terrestrial laser scanner (TLS) echo and three sediment fractions; (A) sand fraction, (B) silt fraction and (C) clay fraction. The logarithmic fitting curves were calculated based on all sediment data that collected in the experimental and monthly sites, and the 95% confidence intervals are also indicated.

−9.39% and 5.01%, but the mean of all absolute errors was also as high as 27.28% and 21.75% (Table 4; Fig. 7).

DISCUSSION

Physical meaning of the coefficients in the inversion equations

The sand fraction in the Nanhui tidal flat gradually decreases seaward, while the silt fraction increases. The clay fraction is only around 5%. The grain size increases shoreward and to the east. Areas with low elevation are characterized by fine-grained sediments carried by tidal currents, due to the retention effect of the breakwater. These different sedimentary environments are an excellent test for determining the relationships between sediment parameters and TLS waveform amplitudes (Collin *et al.*, 2010; Medjkane *et al.*, 2018). Sand/silt fractions and average/median grain size showed a significant logarithmic correlation with TLS waveform amplitudes. A significant logarithmic relationship was also found between the corrected waveform amplitudes and waveform widths. This relationship can be used for future sediment classifications (Fig. S3).

The determined relationships provide the opportunity to explore sedimentological variations in different seasons. To do that, the logarithmic fitting equations ($y = a*\ln(x)+b$) and their coefficients for 15 monthly sampling data were analyzed separately (Table S1). In general, the larger the correlation coefficient, the higher is the absolute value of the parameter a, which means that the logarithm curve declines faster. As a result, our data suggest that the variation in average grain size is greater in winter (Fig. 8A). At the same time, the parameter b increases with an increase in the correlation coefficient, indicating that coarser grain-size distributions yield a better fit (Fig. 8B). The larger the bottom slope, the smaller is the correlation coefficient, indicating that slope steepening due to erosion in summer produces coarser sediment grain size along the transect (Fig. 8C). The relationship between parameters a and b and intertidal slope reflect the above variation differences of coefficients a and b (Fig. 8D and E). In winter, weaker wave forcing and lower mean tidal levels reduce the

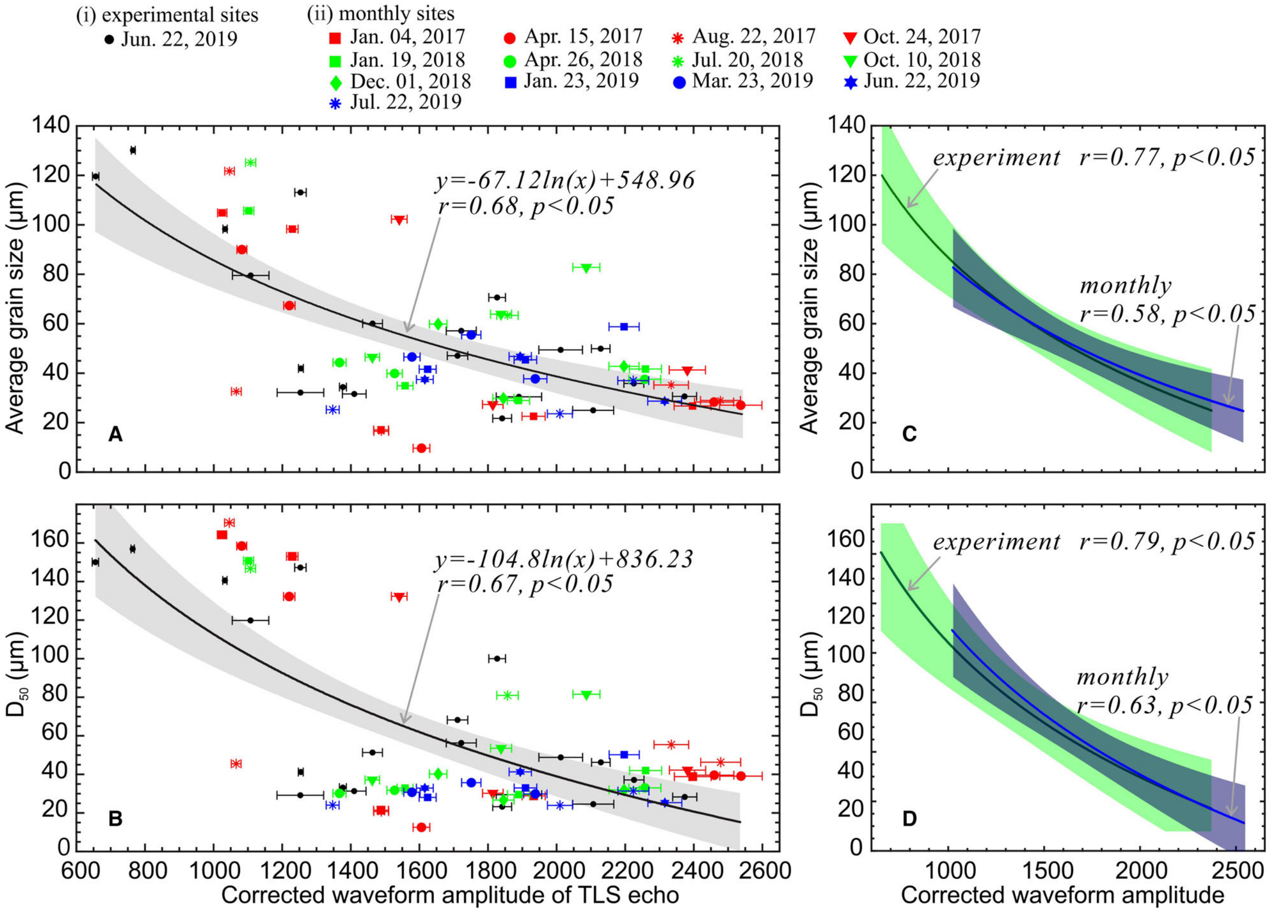

Fig. 6. Relationships between the corrected waveform amplitudes of terrestrial laser scanner (TLS) echo and the (A) sediment average grain size and (B) sediment D_{50}. The different logarithmic fitting curves and related confidence intervals for experiment and monthly sediments are shown in (C) for sediment average grain size and (D) for sediment D_{50}.

deposition of fine sediments, leading to smaller variations in grain size along transect m1–m5. To conclude, the parameters *a* and *b* in the logarithmic fitting equation are related to seasonal hydrodynamic conditions that control the spatial regularity of sediment characteristics. Despite seasonal variations, sediment parameters and corrected TLS waveform amplitudes maintain significant logarithmic relationships (Figs 5 and 6).

Validation and possible sources of uncertainty

A subset of monthly sediment samples was used to validate the logarithmic relationships for sand and silt fractions, average grain size and D_{50}. The relationships derived from the validation data compare well to the relationships derived from the experimental and monthly data (Fig. 9A to D), indicating the effectiveness and robustness of the TLS-based method. Moreover, the sediment parameters derived from the logarithmic equations of the validation data were compared with the values measured in the laboratory (Fig. 9E to H). The *RMSEs* of sand fraction, silt fraction, average grain size and D_{50} are 17.17%, 16.68%, 24.86 μm and 33.06 μm (Fig. 9E to H), which differ from the values of experimental and monthly collected sediments by −14.57%, −12.85%, 9.60% and −4.33%, respectively. The difference in *MADs* is even lower: −7.43%, −9.40%, 13.94% and 0.86%, respectively (Fig. 9E to H); the study results and the validation results are therefore consistent.

Previous studies have shown that sandy sediments in the Yangtze Delta have a terrestrial origin with terrigenous detrital minerals (mainly quartz and feldspar); the substrate material of

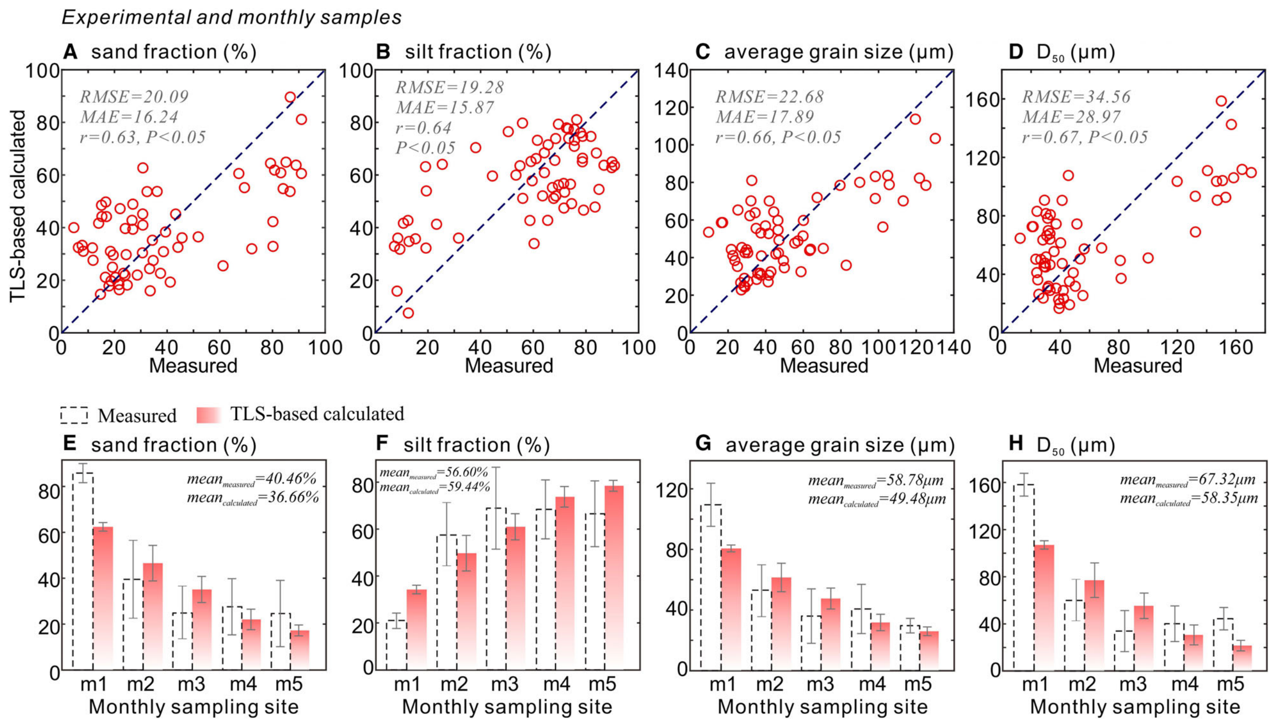

Fig. 7. Comparison of sediment parameters (sand fraction, silt fraction, average grain size and D_{50}) measured in the laboratory and calculated from terrestrial laser scanner (TLS); the calculated results were based on the log-fitting equations between the corrected waveform amplitudes of TLS echo and sediment parameters. (A) to (D) All experimental and monthly sediment samples; (E) to (F) at five monthly sampling sites, standard deviations are also indicated.

the Nanhui tidal flat is consistent with those data (Cao *et al.*, 2018). Sandy substrates of tidal flats are relatively loose with high porosity, and are eroded by waves during flooding (especially in summer). On the other hand, silty/clay sediments are mainly composed of clay minerals (illite, kaolinite and chlorite, etc.), which is widely distributed in the Nanhui tidal flat and the Yangtze Delta. Because fine-grained minerals adhere together, the porosity is smaller, and the backscattering of the near-infrared laser stronger (Burton *et al.*, 2011). Sediment distribution in this tidal flat is dominated by intertidal hydrodynamics and disturbances from the breakwater or marsh vegetation (Figs 1C and 3A to D). Differences in echo intensity were also used in other studies of sediment identification and classification (Brennan & Webster, 2006; Tulldahl & Wikström, 2012; Fabbri *et al.*, 2017).

Microphytobenthos (for example, cyanobacterial mats or diatom biofilms) can also alter the properties of sediments with their extracellular polymeric substance (EPS) that adheres to sediment surfaces (Jorge & Beusekom, 1995; Méléder *et al.*, 2005; Andersen *et al.*, 2010). The EPS thickness is comparable to the diameter of fine sand (Herlory *et al.*, 2004; Stal, 2010), thus possibly affecting the TLS echo intensity. The effect of microphytobenthos requires further detailed investigations. In our study area, the wave action is strong, favouring coarse bottom sediments with low water content (Zhu *et al.*, 2014; Wei *et al.*, 2020). Tidal flat has been eroded by about 80 to 100 cm since 2016, and the erosional regime has likely prevented the formation of microphytobenthos in recent years (Figs S4 and S5; Wang *et al.*, 2018). Therefore, the sediments at our site are coarse-grained sand or sandy silty sand with a tendency to further coarsening (Fig. 3; Wei *et al.*, 2020). van de Koppel *et al.* (2001) studied the positive feedback between the development processes of benthic diatoms and the erosion of silty sediments in the Molenplaat tidal flat of the Westerschelde Estuary, Netherlands. They pointed out that when the erosion was present with high bed shear stress, the diatom cover was low. Garwood *et al.* (2015) also indicated that biofilms are

Table 4. Comparison of measured and terrestrial laser scanner (TLS) based sediment fractions (sand, silt and clay), average grain size, and D_{50} of surface sediments. Monthly measurements at different sampling sites.

	Site	m1	m2	m3	m4	m5	Mean of all absolute errors	Mean of all sampling sites
Sand fraction	Measured (%)	85.81	39.50	24.83	27.56	24.61	/	40.46
	Calculated (%)	62.38	46.56	35.09	22.04	17.25	/	36.66
	Error (%)	**−27.30**	**17.87**	**41.32**	**−20.03**	**−29.91**	**27.28**	**−9.39**
Silt fraction	Measured (%)	21.66	57.47	68.92	68.41	66.53	/	56.6
	Calculated (%)	34.23	49.74	60.98	73.77	78.46	/	59.44
	Error (%)	**58.03**	**−13.45**	**−11.52**	**7.84**	**17.93**	**21.75**	**5.01**
Clay fraction	Measured (%)	3.53	3.03	3.18	2.79	8.86	/	4.28
	Calculated (%)	2.66	2.91	3.09	3.29	5.87	/	3.56
	Error (%)	**−24.65**	**−3.96**	**−2.83**	**17.92**	**−33.75**	**16.62**	**−16.69**
Average grain size	Measured (μm)	109.48	53.08	35.99	40.69	29.67	/	58.78
	Calculated (μm)	80.65	61.48	47.58	31.76	25.95	/	49.48
	Error (%)	**−26.33**	**15.83**	**32.20**	**−21.95**	**−12.54**	**21.77**	**−7.99**
D_{50}	Measured (μm)	158.13	59.92	33.93	40.17	44.45	/	67.32
	Calculated (μm)	107.02	77.08	55.38	30.68	21.61	/	58.35
	Error (%)	**−32.32**	**28.64**	**63.22**	**−23.62**	**−51.38**	**39.83**	**−13.32**

mainly preserved in fine sediments (clays or very fine silts) in the intertidal flats of the of the Bay of Fundy, Canada. Moreover, Mariotti & Fagherazzi (2012) proposed a biofilm growth model in shallow coastal areas and found that the biofilm mass was affected by strong tidal forcing and wave power, with energetic conditions greatly restricting biofilm growth.

Indeed, the existence of microphytobenthos contributes to the biostabilization of tidal flats by increasing the erosion threshold (Wooldridge *et al.*, 2018; Kim *et al.*, 2021). However, the growth and total mass of microphytobenthos in eroding tidal flats is limited. Since the tidal forcing and wave power in the Nanhui tidal flat are strong, there was no obvious large-scale presence of microphytobenthos during all observation periods in our study area. Therefore, it is speculated that the impact of microphytobenthos on TLS echo intensity is relatively limited in the studied area. However, it must be carefully considered that in other locations, where biota and bedforms are present and the material is muddier, this TLS-based method may not work well.

Intertidal microtopography (for example, sand ripples) may also affect TLS measurements. Both microphytobenthos and bedforms could in theory selectively change the TLS echo intensity as a function of grain size. Ripples are only present in non-cohesive sediments, increasing the roughness of the substrate. Microphytobenthos are more common in cohesive bottom sets, giving rise to biofilm patches. This notwithstanding, the relationships between TLS echo intensity and grain-size parameters are significant at our study site, indicating that important information can still be derived about bottom grain size, and microphytobenthos and bedforms can be treated as possible sources of error. More experiments are clearly needed to address the effect of these processes on grain-size distribution and reduce the uncertainty of the measurements.

Other challenges in detecting surface sediments in tidal flats need to be recognized, such as the influence of vegetation and ponds. A dense vegetation canopy can obstruct the laser beam, thereby reducing the number of echoes bouncing from the substrate (Schmid *et al.*, 2011; Ward *et al.*, 2013; Rayner *et al.*, 2021). The laser signal cannot penetrate ponding water. In these cases, manual samplings are still required to compensate for the absence of TLS data. It is also crucial to establish separate relationships for sediment grain parameters in bare flats and sheltered areas, where vegetation and biofilms are more common.

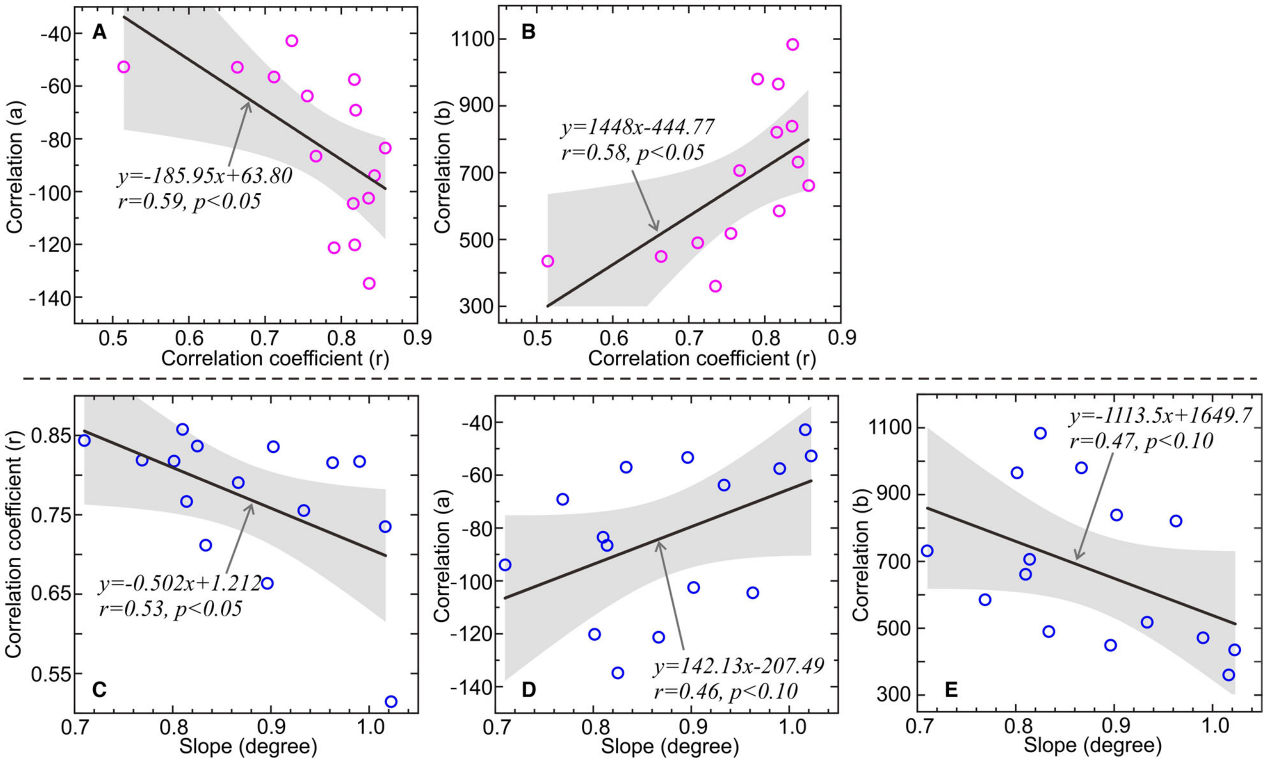

Fig. 8. A logarithm fitting equation $y = a * \ln(x) + b$ was used to determine relationship between corrected waveform amplitude and sediment average grain size, specific results are shown in Table S1. (A) and (B) Relationship between correlation coefficient (r) and parameters a and b of the logarithm fitting equation. (C) to (E) Relationship between intertidal slope and correlation coefficient (r), parameter a and parameter b, respectively.

Factors controlling waveform amplitude of TLS echo

Robust corrections of waveform amplitudes or echo intensities are critical for the proposed TLS method. Multiple potential influencing factors must be considered, which relate to operation stability of the TLS instrumental sensors, atmospheric conditions (transparency, humidity, etc.) and backscattering characteristics of surface sediments (Hopkinson *et al.*, 2004; Yoon *et al.*, 2008; Hancock *et al.*, 2015). Here, the experimental, monthly and validation TLS observations were all carried out in fair weather, with clear sky and low tidal levels. Hence, the intensity attenuation during atmospheric transmission can be ignored. This study only corrected for waveform amplitudes and differences in echo intensities caused by distance and beam angle, and analyzed laser scattering characteristics that are directly associated with the physical organization of intertidal sediments.

Because the TLS (Riegl VZ-4000) operates in the near-infrared band, water content will absorb part of the laser energy (Ehret *et al.*, 1993; Hartzell *et al.*, 2014). Both Unmanned Aerial Vehicle images and original TLS point cloud data showed that there are some wet areas in the Nanhui intertidal flat (Fig. 1C to D); and the actual measurements indicate that water content in the samples was about 17.89% to 34.51%. Therefore, in this study sampling sites without water accumulation were chosen, and the same position of the TLS tripod on the seawall was maintained for all 22 measurements. Further research is needed to explore the attenuation effect of water absorption on the echo waveform amplitude (Nield *et al.*, 2014). In addition, TLS observation is also restricted by tidal hydrodynamic conditions. Because tidal flats are generally affected by wetting and drying, the substrate is only exposed during low tide with the least water accumulation (Choi *et al.*, 2010; Fairley *et al.*, 2018). As a result, the time suitable for observation is relatively short. In the future, it will be necessary to explore the use of airborne LiDAR due to its large-scale and long-distance detection capabilities (Lang &

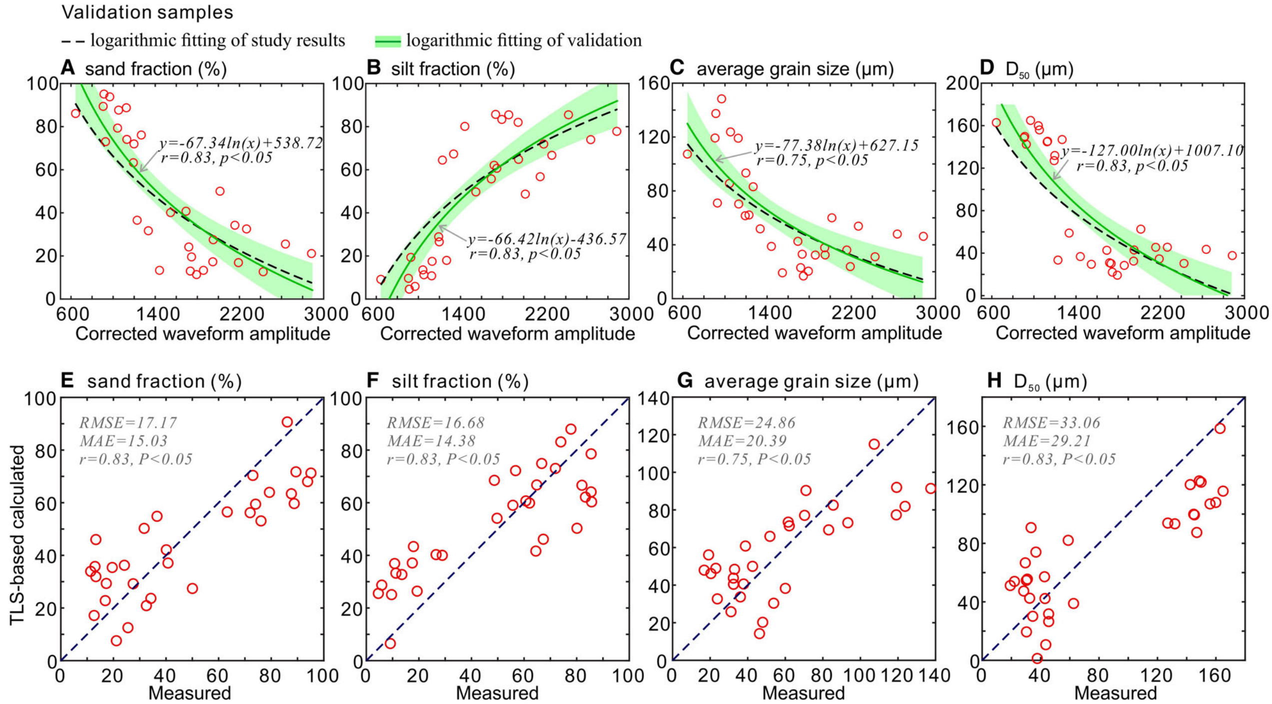

Fig. 9. (A) to (D) Logarithmic fittings between the corrected waveform amplitudes of terrestrial laser scanner (TLS) echo and different sediment fractions and grain sizes; these validation data were collected independently of experimental and monthly samples, and then compared with the study results. (E) and (F) Comparison of measured and TLS-based sediment parameters (sand fraction, silt fraction, average grain size and D_{50}), calculated results were based on the log-fitting equations derived in this study.

McCarty, 2009; Richard Allen *et al.*, 2013; Chardon *et al.*, 2020).

Application of the new TLS method to study intertidal dynamics

With an interpolation of all experimental sediment samples the spatial distribution of average grain size in the Nanhui tidal flat was obtained in June 2019 (Fig. 10A). A similar distribution was obtained from the TLS data using the logarithmic equations developed in this paper (Fig. 10B). Both of these distributions indicate that sediments become gradually finer seaward with the presence of longitudinal subzones. Average grain-size patterns are similar in the collected sediments and in the TLS-based inversion map, with a corresponding mean grain size of 66.43 μm and 65.07 μm, respectively (error of 2.05%; Fig. 10A and B). The measured and TLS-based average grain size have a significant correlation ($r = 0.88$, $P < 0.01$) with a Root Mean Square Error of 13.83 μm. The comparison shows that the TLS method tends to overestimate the average grain size of sediments in the high value interval (Fig. 10C). Since the measured distribution is derived through interpolation of 20 sampling points in a grid, the maximum deviation between measured and calculated values is at both ends of the transects (Fig. 10C). The sediment map was also derived from TLS data collected in January 2019 (Fig. 10D). The average grain size was 71.46 μm, which means that sediments are coarser in winter. Frequency distributions also indicate that the sand fraction increases and the silt fraction decreases in winter (Fig. 10E).

Although the difference between measured and calculated grain-size parameters was relatively high (Figs 5, 6 and 7A to D), the TLS-based method shows an acceptable spatial distribution pattern of average grain size in the study area (Fig 10A to C). This is because, in the Nanhui tidal flat, the distribution of sediment grain-size parameters and their TLS echo intensities are relatively continuous and smooth. The TLS approach provides new opportunities for the determination of

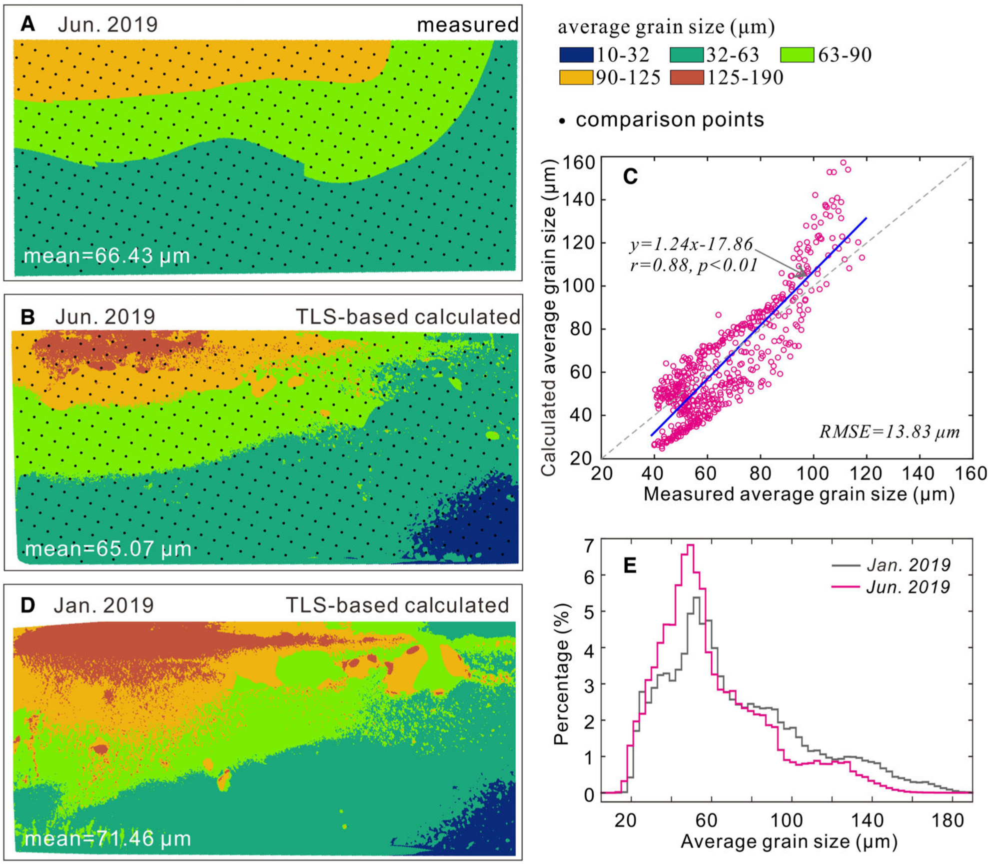

Fig. 10. (A) spatial distribution of sediment average grain size in June 2019 derived from laboratory analyses, (B) derived from terrestrial laser scanner (TLS). A total of 550 equally spaced points were generated to analyze the difference between the two distributions. (C) Relationship between measured and TLS-based average grain sizes. (D) TLS-based average grain sizes in January 2019 and (E) frequency distribution of TLS-based results in January and June 2019.

sediment characteristics in tidal environment, but there are still some technical limitations (correction algorithms, presence of biota) that need to be addressed, especially in specific micro-topographic conditions. The new method does not require repetitive sediment samplings in the field and time-consuming analyses in the laboratory (Flemming, 2007; Ahn, 2012; Park, 2019). Furthermore, traditional methods cannot determine variations in sediment characteristics at high spatial resolution because of the limited number of sampling sites.

More detailed laboratory experiments are needed to clarify the effects of different mineral components on laser backscatter characteristics. The parameters of the logarithmic fitting curves are related to the seasonal sedimentary dynamics and morphodynamic processes. Moreover, our proposed method can be used to explore relationships between sediment grain size and other geophysical and environmental processes, such as wave bottom shear stresses, elevation, nutrients and soil carbon pools (Rosser *et al.*, 2005; van Leeuwen *et al.*, 2011; Ghinassi *et al.*, 2018b; Brand *et al.*, 2019; Wiggins *et al.*, 2019).

CONCLUSIONS

The sediment characteristics of deltaic tidal flats are affected by complex hydrodynamics. In this study, a high-precision full-waveform Terrestrial Laser Scanner (TLS) was used to determine sediment parameters in the Nanhui tidal flat, Yangtze Delta, China. Surface sediment samples were collected from the tidal flat and their grain-size distributions were compared to corresponding corrected waveform amplitudes of TLS echo in different hydrometeorological scenarios, for a total of 22 months. The main results and conclusions are as follows:

(i) The sediment sand fraction, average grain size and D_{50} decrease seaward, while the corrected waveform amplitude of TLS echo increases. This spatial variation is consistent with a decrease in elevation in the Nanhui tidal flat.

(ii) Based on the data, logarithmic equations were constructed to retrieve sediment grain size (fractions, average and D_{50}) from detected TLS waveform amplitudes. The mean of measured and TLS-based calculated average grain size in five sites along the sampling transect was 58.78 μm and 49.48 μm, while the mean D_{50} was 67.32 μm and 58.35 μm. Overall, the errors in the mean value of grain-size parameters along the transect were small, but the absolute value of the error at each sampling site was relatively high.

(iii) The parameters of the proposed logarithmic equations are affected by the spatial regularity of the grain-size distributions. In winter, the weaker hydrodynamic conditions and the gentle geomorphic slopes result in high fitting correlations.

The specificity of the current study area, characterized by energetic hydrodynamics and coarse-grained sediments, must be carefully recognized. This TLS-based method may not work very well in other tidal flats, where microphytobenthos (for example, cyanobacterial mats or diatom biofilms) are present and the substrate is muddier, or in areas where salt marsh vegetation is present. In future studies, specific experiments will be conducted to understand the factors affecting the relationship between TLS waveform amplitude and sediment physical characteristics, so that this relationship can be applied to other types of tidal flats. Grain-size distributions obtained from the new TLS method can be used as indicators of sedimentary dynamics, shedding light on environmental processes affecting biological habitats.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author (Prof. Zhijun Dai) upon reasonable request. Other data elucidating the findings of this study are provided in Supplementary Information files.

REFERENCES

Ahn, J.H. (2012) Size distribution and settling velocities of suspended particles in a tidal embayment. *Water Res.*, **46** (10), 3219–3228.

Andersen, T.J., **Lanuru, M.**, **Van Bernem, C.**, **Pejrup, M.** and **Riethmueller, R.** (2010) Erodibility of a mixed mudflat dominated by microphytobenthos and Cerastoderma edule, East Frisian Wadden Sea, Germany. *Estuar. Coast. Shelf Sci.*, **87**(2), 197–206.

Baumfalk, Y.A. (1979) Heterogeneous grain size distribution in tidal flat sediment caused by bioturbation activity of Arenicola marina (Polychaeta). *Netherlands J. Sea Res.*, **13** (3–4), 428–440.

Beck, M., **Dellwig, O.**, **Liebezeit, G.**, **Schnetger, B.** and **Brumsack, H.J.** (2008) Spatial and seasonal variations of sulphate, dissolved organic carbon, and nutrients in deep pore waters of intertidal flat sediments. *Estuar. Coast. Shelf Sci.*, **79**(2), 307–316.

Beuselinck, L., **Govers, G.**, **Poesen, J.**, **Degraer, G.** and **Froyen, L.** (1998) Grain-size analysis by laser diffractometry: comparison with the sieve-pipette method. *Catena*, **32**(3–4), 193–208.

Bitelli, G., **Dubbini, M.** and **Zanutta, A.** (2004) Terrestrial laser scanning and digital photogrammetry techniques to monitor landslide bodies. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, **35**(B5), 246–251.

Bos, A.R., **Bouma, T.J.**, **de Kort, G.L.** and **van Katwijk, M.M.** (2007) Ecosystem engineering by annual intertidal seagrass beds: sediment accretion and modification. *Estuar. Coast. Shelf Sci.*, **74**(1–2), 344–348.

Brand, E., **De Sloover, L.**, **De Wulf, A.**, **Montreuil, A.L.**, **Vos, S.** and **Chen, M.** (2019) Cross-shore suspended sediment transport in relation to topographic changes in the intertidal zone of a macro-tidal beach (Mariakerke, Belgium). *J. Mar. Sci. Eng.*, **7**(6), 172.

Brennan, R. and **Webster, T.L.** (2006) Object-oriented land cover classification of lidar-derived surfaces. *Can. J. Remote Sens.*, **32**(2), 162–172.

Brodu, N. and **Lague, D.** (2012) 3D terrestrial lidar data classification of complex natural scenes using a multi-scale dimensionality criterion: applications in geomorphology. *ISPRS-J. Photogramm. Remote Sens.*, **68**, 121–134.

Burns, J. and **Lück-Vogel, M.** (2017) Using LiDAR derivatives to estimate sediment grain size on beaches in False Bay. International Symposium for Remote Sensing of the Environment, Tshwane, South Africa, May 8–12, 2017.

Burton, D., **Dunlap, D.B.**, **Wood, L.J.** and **Flaig, P.P.** (2011) Lidar intensity as a remote sensor of rock properties. *J. Sediment. Res.*, **81**(5), 339–347.

Cao, C., **Cai, F.**, **Zheng, Y.L.**, **Wu, C.Q.**, **Lu, H.Q.**, **Bao, J.J.** and **Sun, Q.** (2018) Temporal and spatial characteristics of sediment sources on the southern Yangtze Shoal over the Holocene. *Sci. Rep.*, **8**(1), 1–12.

Carbonneau, P.E., **Lane, S.N.** and **Bergeron, N.E.** (2004) Catchment-scale mapping of surface grain size in gravel bed rivers using airborne digital imagery. *Water Resour. Res.*, **40**(7), 1–11.

Chardon, V., **Schmitt, L.**, **Piégay, H.** and **Lague, D.** (2020) Use of terrestrial photosieving and airborne topographic LiDAR to assess bed grain size in large rivers: a study on the Rhine River. *Earth Surf. Process. Landf.*, **45**(10), 2314–2330.

Chauve, A., **Mallet, C.**, **Bretar, F.**, **Durrieu, S.**, **Deseilligny, M.P.** and **Puech, W.** (2008) Processing full-waveform lidar data: modelling raw signals. In: *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 2007*, pp. 102–107.

Choi, J.K., **Eom, J.** and **Ryu, J.H.** (2011) Spatial relationships between surface sedimentary facies distribution and topography using remotely sensed data: example from the Ganghwa tidal flat, Korea. *Mar. Geol.*, **280**(1–4), 205–211.

Choi, J.K., **Ryu, J.H.**, **Lee, Y.K.**, **Yoo, H.R.**, **Woo, H.J.** and **Kim, C.H.** (2010) Quantitative estimation of intertidal sediment characteristics using remote sensing and GIS. *Estuar. Coast. Shelf Sci.*, **88**(1), 125–134.

Coco, G., **Zhou, Z.**, **Van Maanen, B.**, **Olabarrieta, M.**, **Tinoco, R.** and **Townend, I.** (2013) Morphodynamics of tidal networks: advances and challenges. *Mar. Geol.*, **346**, 1–16.

Collin, A., **Long, B.** and **Archambault, P.** (2010) Salt-marsh characterization, zonation assessment and mapping through a dual-wavelength LiDAR. *Remote Sens. Environ.*, **114**(3), 520–530.

Conesa-García, C., **Puig-Mengual, C.**, **Riquelme, A.**, **Tomás, R.**, **Martínez-Capel, F.**, **García-Lorenzo, R.**, **Pastor, J.L.**, **Pérez-Cutillas, P.** and **Cano Gonzalez, M.** (2020) Combining SfM photogrammetry and terrestrial laser scanning to assess event-scale sediment budgets along a gravel-bed ephemeral stream. *Remote Sens.*, **12**(21), 3624.

Dai, Z.J., **Liu, J.T.** and **Wen, W.** (2015) Morphological evolution of the south passage in the Changjiang (Yangtze River) estuary, China. *Quat. Int.*, **380**, 314–326.

De Jorge, V.N. and **van Beusekom, J.E.E.** (1995) Wind- and tide-induced resuspension of sediment and microphytobenthos from tidal flats in the Ems estuary. *Limnol. Oceanogr.*, **40**(4), 776–778.

Deronde, B., **Houthuys, R.**, **Henriet, J.P.** and **Lancker, V.V.** (2008) Monitoring of the sediment dynamics along a sandy shoreline by means of airborne hyperspectral remote sensing and LIDAR: a case study in Belgium. *Earth Surf. Processes Landforms*, **33**(2), 280–294.

Diaz-Gomez, R., **Pasternack, G.B.**, **Guillon, H.**, **Byrne, C.F.** and **Sandoval Solis, S.** (2019) Can airborne lidar point clouds quantify grain size contributions to ground sediment facies? AGU Fall Meeting Abstracts, EP11C-2137.

Donnelly, J.P. and **Bertness, M.D.** (2001) Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. *Annu. Rev. Earth Planet. Sci.*, **98** (25), 14218–14223.

Ehret, G., **Kiemle, C.**, **Renger, W.** and **Simmet, G.** (1993) Airborne remote sensing of tropospheric water vapor with a near–infrared differential absorption lidar system. *Appl. Opt.*, **32**(24), 4534–4551.

Engin, I.C. and **Maerz, N.H.** (2019) Size distribution analysis of aggregates using LiDAR scan data and an alternate algorithm. *Measurement*, **143**, 136–143.

Eren, F., **Pe'eri, S.**, **Rzhanov, Y.** and **Ward, L.** (2018) Bottom characterization by using airborne lidar bathymetry (ALB) waveform features obtained from bottom return residual analysis. *Remote Sens. Environ.*, **206**, 260–274.

Evans, G. (1965) Intertidal flat sediments and their environments of deposition in the Wash. *Q. J. Geol. Soc. Lond.*, **121**(1–4), 209–240.

Fabbri, S., **Giambastiani, B.M.**, **Sistilli, F.**, **Scarelli, F.** and **Gabbianelli, G.** (2017) Geomorphological analysis and classification of foredune ridges based on Terrestrial Laser Scanning (TLS) technology. *Geomorphology*, **295**, 436–451.

Fagherazzi, S., **Kirwan, M.L.**, **Mudd, S.M.**, **Guntenspergen, G.R.**, **Temmerman, S.**, **D'Alpaos, A.**, **Van De Koppel, J.**, **Rybczyk, J.M.**, **Reyes, E.**, **Craft, C.** and **Clough, J.** (2012) Numerical models of salt marsh evolution: ecological, geomorphic, and climatic factors. *Rev. Geophys.*, **50**(1), 1–28.

Fairley, I., **Mendzil, A.**, **Togneri, M.** and **Reeve, D.E.** (2018) The use of unmanned aerial systems to map intertidal sediment. *Remote Sens.*, **10**(12), 1918.

Fan, D.D., **Wu, Y.J.**, **Zhang, Y.**, **Burr, G.**, **Huo, M.** and **Li, J.** (2017) South flank of the Yangtze delta: past, present, and future. *Mar. Geol.*, **392**, 78–93.

FitzGerald, D.M., **Fenster, M.S.**, **Argow, B.A.** and **Buynevich, I.V.** (2008) Coastal impacts due to sea-level rise. *Annu. Rev. Earth Planet. Sci.*, **36**(1), 601–647.

Flemming, B.W. (2007) The influence of grain-size analysis methods and sediment mixing on curve shapes and textural parameters: implications for sediment trend analysis. *Sediment. Geol.*, **202**(3), 425–435.

Folk, R.L. and **Ward, W.C.** (1957) A study in the significance of grain size parameters. *J. Sediment. Res.*, **27**(1), 3–26.

Friedrichs, C.T. and **Perry, J.E.** (2001) Tidal salt marsh morphodynamics: a synthesis. *J. Coast. Res.*, 7–37.

Fu, G., **Li, J.**, **Ying, M.** and **Yu, Z.** (2007) Analysis on recent topography evolution of Nanhuizui tidal flat in Yangtze Estuary. *Mar. Sci. Bull.*, **26**(2), 105–112.

Gade, M., **Alpers, W.**, **Melsheimer, C.** and **Tanck, G.** (2008) Classification of sediments on exposed tidal flats in the German Bight using multi-frequency radar data. *Remote Sens. Environ.*, **112**(4), 1603–1613.

Gartner, J.W., **Cheng, R.T.**, **Wang, P.F.** and **Richter, K.** (2001) Laboratory and field evaluations of the LISST-100 instrument for suspended particle size determinations. *Mar. Geol.*, **175**(1–4), 199–219.

Garwood, J.C., **Hill, P.S.**, **MacIntyre, H.L.** and **Law, B.A.** (2015) Grain sizes retained by diatom biofilms during erosion on tidal flats linked to bed sediment texture. *Cont. Shelf Res.*, **104**, 37–44.

Ghinassi, M. (2007) The effects of differential subsidence and coastal topography on high-order transgressive-regressive cycles: Pliocene nearshore deposits of the Val d'Orcia Basin, Northern Apennines, Italy. *Sediment. Geol.*, **202**(4), 677–701.

Ghinassi, M., **Brivio, L.**, **D'Alpaos, A.**, **Finotello, A.**, **Carniello, L.**, **Marani, M.** and **Cantelli, A.** (2018a) Morphodynamic evolution and sedimentology of a microtidal meander bend of the Venice Lagoon (Italy). *Mar. Pet. Geol.*, **96**, 391–404.

Ghinassi, M., **D'alpaos, A.**, **Gasparotto, A.**, **Carniello, L.**, **Brivio, L.**, **Finotello, A.**, **Roner, M.**, **Franceschinis, E.**, **Realdon, N.**, **Howes, N.** and **Cantelli, A.** (2018b) Morphodynamic evolution and stratal architecture of translating tidal point bars: inferences from the northern Venice Lagoon (Italy). *Sedimentology*, **65**(4), 1354–1377.

Guarnieri, A., **Vettore, A.**, **Pirotti, F.**, **Menenti, M.** and **Marani, M.** (2009) Retrieval of small-relief marsh morphology from Terrestrial Laser Scanner, optimal spatial filtering, and laser return intensity. *Geomorphology*, **113**(1–2), 12–20.

Hakala, T., **Suomalainen, J.**, **Kaasalainen, S.** and **Chen, Y.W.** (2012) Full waveform hyperspectral LiDAR for terrestrial laser scanning. *Opt. Express*, **20**(7), 7119–7127.

Hancock, S., **Armston, J.**, **Li, Z.**, **Gaulton, R.**, **Lewis, P.**, **Disney, M.**, **Danson, F.M.**, **Strahler, A.**, **Schaaf, C.**, **Anderson, K.** and **Gaston, K.J.** (2015) Waveform lidar over vegetation: an evaluation of inversion methods for estimating return energy. *Remote Sens. Environ.*, **164**, 208–224.

Hartzell, P., **Glennie, C.**, **Biber, K.** and **Khan, S.** (2014) Application of multispectral LiDAR to automated virtual outcrop geology. *ISPRS-J. Photogramm. Remote Sens.*, **88**, 147–155.

Herlory, O., **Guarini, J.M.**, **Richard, P.** and **Blanchard, G.F.** (2004) Microstructure of microphytobenthic biofilm and its spatio-temporal dynamics in an intertidal mudflat (Aiguillon Bay, France). *Mar. Ecol. Prog. Ser.*, **282**, 33–44.

Herman, P.M., **Middelburg, J.J.** and **Heip, C.H.** (2001) Benthic community structure and sediment processes on an intertidal flat: results from the ECOFLAT project. *Cont. Shelf Res.*, **21**(18–19), 2055–2071.

Höfle, B. and **Pfeifer, N.** (2007) Correction of laser scanning intensity data: data and model-driven approaches. *ISPRS-J. Photogramm. Remote Sens.*, **62**(6), 415–433.

Hopkinson, C., **Chasmer, L.**, **Young-Pow, C.** and **Treitz, P.** (2004) Assessing forest metrics with a ground-based scanning lidar. *Can. J. For. Res.*, **34**(3), 573–583.

Jiang, W., **Li, J.**, **Wang, W.**, **Xie, Z.** and **Mai, S.** (2005) Assessment of wetland ecosystem health based on RS and GIS in Liaohe River Delta. In *Proceedings. 2005 IEEE International Geoscience and Remote Sensing Symposium.*, pp. 2384–2386.

Kane, I.A., **McCaffrey, W.D.** and **Peakall, J.** (2008) Controls on sinuosity evolution within submarine channels. *Geology*, **36**(4), 287–290.

Kane, I.A. and **Pontén, A.S.** (2012) Submarine transitional flow deposits in the Paleogene Gulf of Mexico. *Geology*, **40** (12), 1119–1122.

Kashani, A.G., **Olsen, M.J.**, **Parrish, C.E.** and **Wilson, N.** (2015) A review of LiDAR radiometric processing: from ad hoc intensity correction to rigorous radiometric calibration. *Sensors*, **15**(11), 28099–28128.

Kim, B., **Lee, J.**, **Noh, J.**, **Bae, H.**, **Lee, C.**, **Ha, H.J.**, **Hwang, K.**, **Kim, D.U.**, **Kwonc, B.O.**, **Ha, H.K.**, **Pierred, G.**, **Delattred, C.**, **Michaud, P.** and **Khim, J.S.** (2021) Spatiotemporal variation of extracellular polymeric substances (EPS) associated with the microphytobenthos of tidal flats in the Yellow Sea. *Mar. Pollut. Bull.*, **171**, 112780.

Kim, K.L., **Kim, B.J.**, **Lee, Y.K.** and **Ryu, J.H.** (2019) Generation of a large-scale surface sediment classification map using unmanned aerial vehicle (UAV) data: a case study at the Hwang-do tidal flat, Korea. *Remote Sens.*, **11** (3), 229.

Koenig, K., **Höfle, B.**, **Hämmerle, M.**, **Jarmer, T.**, **Siegmann, B.** and **Lilienthal, H.** (2015) Comparative classification analysis of post-harvest growth detection from terrestrial LiDAR point clouds in precision agriculture. *ISPRS-J. Photogramm. Remote Sens.*, **104**, 112–125.

Komar, P.D. and **Cui, B.** (1984) The analysis of grain-size measurements by sieving and settling-tube techniques. *J. Sediment. Res.*, **54**(2), 603–614.

Konert, M. and **Vandenberghe, J.E.F.** (1997) Comparison of laser grain size analysis with pipette and sieve analysis: a solution for the underestimation of the clay fraction. *Sedimentology*, **44**(3), 523–535.

van de Koppel, J., **Herman, P.M.**, **Thoolen, P.** and **Heip, C.H.** (2001) Do alternate stable states occur in natural ecosystems? Evidence from a Tidal flat. *Ecology*, **82**(12), 3449–3461.

Lang, M.W. and **McCarty, G.W.** (2009) Lidar intensity for improved detection of inundation below the forest canopy. *Wetlands*, **29**(4), 1166–1178.

Law, B.A., **Milligan, T.G.**, **Hill, P.S.**, **Newgard, J.**, **Wheatcroft, R.A.** and **Wiberg, P.L.** (2013) Flocculation on a muddy intertidal flat in Willapa Bay, Washington, part I: a regional survey of the grain size of surficial sediments. *Cont. Shelf Res.*, **60**, 136–S144.

van Leeuwen, B., **Augustijn, D.C.**, **Van Wesenbeeck, B.K.**, **Hulscher, S.J.** and **De Vries, M.B.** (2010) Modeling the influence of a young mussel bed on fine sediment dynamics on an intertidal flat in the Wadden Sea. *Ecol. Eng.*, **36**(2), 145–153.

van Leeuwen, M., **Hilker, T.**, **Coops, N.C.**, **Frazer, G.**, **Wulder, M.A.**, **Newnham, G.J.** and **Culvenor, D.S.** (2011) Assessment of standing wood and fiber quality using ground and airborne laser scanning: a review. *For. Ecol. Manage.*, **261**(9), 1467–1478.

Maan, D.C., **van Prooijen, B.C.**, **Wang, Z.B.** and **De Vriend, H.J.** (2015) Do intertidal flats ever reach equilibrium? *J. Geophys. Res. Earth Surf.*, **120**(11), 2406–2436.

Manzo, C., **Valentini, E.**, **Taramelli, A.**, **Filipponi, F.** and **Disperati, L.** (2015) Spectral characterization of coastal sediments using field spectral libraries, airborne hyperspectral images and topographic LiDAR data (FHyL). *Int. J. Appl. Earth Obs. Geoinf.*, **36**, 54–68.

Mariotti, G. and **Fagherazzi, S.** (2012) Modeling the effect of tides and waves on benthic biofilms. *J. Geophys. Res. Biogeosci.*, **117**(G4), 1–14. https://doi.org/10.1029/2012JG002064

McManus, J. (1988) Grain size determination and interpretation. In: *Techniques in Sedimentology* (Ed. Tucker, M.), pp. 63–85. Blackwell, Oxford.

Medjkane, M., **Maquaire, O.**, **Costa, S.**, **Roulland, T.H.**, **Letortu, P.**, **Fauchard, C.**, **Antoine, R.** and **Davidson, R.** (2018) High-resolution monitoring of complex coastal morphology changes: cross-efficiency of SfM and TLS-based survey (Vaches-Noires cliffs, Normandy, France). *Landslides*, **15**(6), 1097–1108.

Méléder, V., **Barillé, L.**, **Rincé, Y.**, **Morançais, M.**, **Rosa, P.** and **Gaudin, P.** (2005) Spatio-temporal changes in microphytobenthos structure analysed by pigment composition in a macrotidal flat (Bourgneuf Bay, France). *Mar. Ecol. Prog. Ser.*, **297**, 83–99.

Munroe, D. and **McKinley, R.S.** (2007) Commercial Manila clam (*Tapes philippinarum*) culture in British Columbia, Canada: the effects of predator netting on intertidal sediment characteristics. *Estuar. Coast. Shelf Sci.*, **72**(1–2), 319–328.

Murray, M.R. (2002) Is laser particle size determination possible for carbonate-rich lake sediments? *J. Paleolimn.*, **27**(2), 173–183.

Neverman, A.J., **Fuller, I.C.**, **Procter, J.N.** and **Death, R.G.** (2019) Terrestrial laser scanning and structure-from-motion photogrammetry concordance analysis for describing the surface layer of gravel beds. *Prog. Phys. Geogr.*, **43**(2), 260–281.

Nield, J.M., **King, J.** and **Jacobs, B.** (2014) Detecting surface moisture in aeolian environments using terrestrial laser scanning. *Aeolian Res.*, **12**, 9–17.

Owers, C.J., **Rogers, K.** and **Woodroffe, C.D.** (2018) Terrestrial laser scanning to quantify above-ground biomass of structurally complex coastal wetland vegetation. *Estuar. Coast. Shelf Sci.*, **204**, 164–176.

Park, C.S. and **Hwang, E.K.** (2011) An investigation of the relationship between sediment particles size and the development of green algal mats (*Ulva prolifera*) on the intertidal flats of Muan, Korea. *J. Appl. Phycol.*, **23**(3), 515–522.

Park, N.W. (2019) Geostatistical integration of field measurements and multi-sensor remote sensing images for spatial prediction of grain size of intertidal surface sediments. *J. Coastal Res.*, **90**(SI), 190–196.

Persson, Å., **Söderman, U.**, **Töpel, J.** and **Ahlberg, S.** (2005) Visualization and analysis of full-waveform airborne laser scanner data. International Archives of Photogrammetry, Remote Sensing and Spatial. *Inf. Sci.*, **36**(3/W19), 103–108.

Rainey, M.P., **Tyler, A.N.**, **Gilvear, D.J.**, **Bryant, R.G.** and **McDonald, P.** (2003) Mapping intertidal estuarine sediment grain size distributions through airborne remote sensing. *Remote Sens. Environ.*, **86**(4), 480–490.

Rayner, D., **Glamore, W.**, **Grandquist, L.**, **Ruprecht, J.**, **Waddington, K.** and **Khojasteh, D.** (2021) Intertidal wetland vegetation dynamics under rising sea levels. *Sci. Total Environ.*, **766**, 144237.

Richard Allen, T., **Wang, Y.** and **Gore, B.** (2013) Coastal wetland mapping combining multi-date SAR and LiDAR. *Geocarto. Int.*, **28**(7), 616–631.

Rosser, N.J., **Petley, D.N.**, **Lim, M.**, **Dunning, S.A.** and **Allison, R.J.** (2005) Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. *Q. J. Eng. Geol. Hydrogeol.*, **38**(4), 363–375.

Schmid, K.A., **Hadley, B.C.** and **Wijekoon, N.** (2011) Vertical accuracy and use of topographic LIDAR data in coastal marshes. *J. Coastal Res.*, **27**(6A), 116–132.

Short, A.D. (1991) Macro-meso tidal beach morphodynamics: an overview. *J. Coast. Res.*, 417–436.

Stal, L.J. (2010) Microphytobenthos as a biogeomorphological force in intertidal sediment stabilization. *Ecol. Eng.*, **36**(2), 236–245.

Sun, Y.M., **Cai, Z.Q.** and **Fu, J.** (2019) Particle morphomics by high-throughput dynamic image analysis. *Sci. Rep.*, **9** (1), 1–11.

Swales, A., **MacDonald, I.T.** and **Green, M.O.** (2004) Influence of wave and sediment dynamics on cordgrass (*Spartina anglica)* growth and sediment accumulation on an exposed intertidal flat. *Estuaries*, **27**(2), 225–243.

Swithenbank, J., **Beer, J.M.**, **Taylor, D.**, **Abbot, D.** and **McCreath, G.C.** (1976) A laser diagnostic technique for the measurement of droplet and particle size distribution. *Progr. Astronaut. Aeronaut*, **53**, 421–447.

Tang, Z.H., **Gu, Y.**, **Dai, Z.J.**, **Li, Y.**, **LaGrange, T.**, **Bishop, A.** and **Drahota, J.** (2015) Examining playa wetland inundation conditions for National Wetland Inventory, Soil Survey Geographic database, and LiDAR data. *Wetlands*, **35**(4), 641–654.

Tang, Z.H., **Li, R.P.**, **Li, X.**, **Jiang, W.G.** and **Hirsh, A.** (2014) Capturing LiDAR-derived hydrologic spatial parameters to evaluate playa wetlands. *J. Am. Water Resour. Assoc.*, **50** (1), 234–245.

Tseng, K.H., **Kuo, C.Y.**, **Lin, T.H.**, **Huang, Z.C.**, **Lin, Y.C.**, **Liao, W.H.** and **Chen, C.F.** (2017) Reconstruction of time-varying tidal flat topography using optical remote sensing imageries. *ISPRS-J. Photogramm. Remote Sens.*, **131**, 92–103.

Tulldahl, H.M. and **Wikström, S.A.** (2012) Classification of aquatic macrovegetation and substrates with airborne lidar. *Remote Sens. Environ.*, **121**, 347–357.

Tysmans, D., **Claeys, P.**, **Deriemaeker, L.**, **Maes, D.**, **Finsy, R.** and **Van Molle, M.** (2006) Size and shape analysis of sedimentary grains by automated dynamic image analysis. *Part. Part. Syst. Charact.*, **23**(5), 381–387.

van Der Wal, D., **Herman, P.M.** and **Wielemaker-van Den Dool, A.** (2005) Characterisation of surface roughness and sediment texture of intertidal flats using ERS SAR imagery. *Remote Sens. Environ.*, **98**(1), 96–109.

Wang, J., **Dai, Z.J.**, **Wei, W.**, **Ge, Z.P.**, **Pang, W.H.**, **Ma, B.B.**, **Mei, X.F.** and **Yu, Y.W.** (2018) LiDAR-based recent morphodynamic study of south Nanhui tidal flat, Changjiang Estuary. *Oceanogr. Limnol.*, **49**(4), 754–768.

Wang, J., **Dai, Z.J.**, **Mei, X.F.** and **Fagherazzi, S.** (2020) Tropical cyclones significantly alleviate mega-deltaic erosion induced by high riverine flow. *Geophys. Res. Lett.*, **47**(19), e2020GL089065.

Wang, X. and **Ke, X.** (1997) Grain size characteristics of the extant tidal flat sediments along the Jiangsu coast, China. *Sediment. Geol.*, **112**(1–2), 105–122.

Ward, R.D., **Burnside, N.G.**, **Joyce, C.B.** and **Sepp, K.** (2013) The use of medium point density LiDAR elevation data to determine plant community types in Baltic coastal wetlands. *Ecol. Indic.*, **33**, 96–104.

Watson, E.B., **Pasternack, G.B.**, **Gray, A.B.**, **Goñi, M.** and **Woolfolk, A.M.** (2013) Particle size characterization of historic sediment deposition from a closed estuarine lagoon, Central California. *Estuar. Coast. Shelf Sci.*, **126**, 23–33.

Wei, W., **Dai, Z.J.**, **Pang, W.H.**, **Wang, J.** and **Gao, S.** (2020) Sedimentary zonation shift of tidal flats in a meso-tidal estuary. *Sediment. Geol.*, **407**, 105749.

Wiggins, M., **Scott, T.**, **Masselink, G.**, **Russell, P.** and **McCarroll, R.J.** (2019) Coastal embayment rotation:

response to extreme events and climate control, using full embayment surveys. *Geomorphology*, **327**, 385–403.

Wooldridge, L.J., **Worden, R.H.**, **Griffiths, J.**, **Utley, J.E.** and **Thompson, A.** (2018) The origin of clay-coated sand grains and sediment heterogeneity in tidal flats. *Sediment. Geol.*, **373**, 191–209.

Yamashita, S., **Nakajo, T.**, **Naruse, H.** and **Sato, T.** (2009) The three-dimensional distribution of sedimentary facies and characteristics of sediment grain size distribution in a sandy tidal flat along the Kushida River estuary, Ise Bay, central Japan. *Sediment. Geol.*, **215**(1–4), 70–82.

Yates, M.G., **Jones, A.R.**, **McGrorty, S.** and **Goss-Custard, J.D.** (1993) The use of satellite imagery to determine the distribution of intertidal surface sediments of the Wash, England. *Estuar. Coast. Shelf Sci.*, **36**(4), 333–344.

Yoo, J.W., **Hwang, I.S.** and **Hong, J.S.** (2007) Inference models for tidal flat elevation and sediment grain size: a preliminary approach on tidal flat microbenthic community. *Ocean Sci. J.*, **42**(2), 69–79.

Yoon, J.S., **Shin, J.I.** and **Lee, K.S.** (2008) Land cover characteristics of airborne LiDAR intensity data: a case study. *IEEE Geosci. Remote Sens. Lett.*, **5**(4), 801–805.

Zhang, C.H., **Wang, L.J.**, **Li, G.S.**, **Dong, S.S.**, **Yang, J.R.** and **Wang, X.L.** (2002) Grain size effect on multi-element concentrations in sediments from the intertidal flats of Bohai Bay, China. *Appl. Geochem.*, **17**(1), 59–68.

Zhu, Q., **Yang, S.L.** and **Ma, Y.X.** (2014) Intra-tidal sedimentary processes associated with combined wave-current action on an exposed, erosional mudflat, southeastern Yangtze River Delta, China. *Mar. Geol.*, **347**, 95–106.

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Supporting Information

Additional information may be found in the online version of this article:

Text S1. Nanhui tidal flat.

Text S2. Working principles of TLS.

Text S3. Sediment pretreatment.

Text S4. Measurements of grain sizes and water contents of surface sediments.

Text S5. Waveform denoising and decomposition.

Text S6. Distance and angle correction of waveform amplitudes.

Text S7. Intertidal geomorphology and substrate slope.

Figure S1. Variations in original LiDAR intensity with different distances to TLS (Riegl VZ-4000), 23 measured points were used on the concrete breakwater.

Figure S2. Relationship between the corrected waveform amplitude of TLS echo and corrected LiDAR intensity of the same experimental sediment sample.

Figure S3. Relationship between the corrected waveform amplitude of the TLS and its width for the experimental sediment samples; the colormap indicates sediment average grain size.

Figure S4. Field photograph of study area, showing the bare tidal flat, the salt marsh and the breakwater.

Figure S5. Intertidal erosion and deposition patterns in the Nanhui tidal flat (from Wang *et al.*, 2018).

Table S1. The coefficients of logarithmic fittings *(y=a*ln(x)+b)* between corrected waveform amplitudes of TLS echo and sediment average grain size, and their correlation coefficients (r) and corresponding intertidal geomorphic slopes at different months.