Simulating the role of tides and sediment characteristics on tidal flat sorting and bedding dynamics

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# Abstract (max. 300)

Understanding sediment sorting and bedding dynamics has high value to unravelling the mechanisms underlying geomorphological, geological, ecological and environmental imprints of tidal wetlands and hence to predicting their future changes. Using the Nanhui tidal flat on the Changjiang (Yangtze) Delta, China, as a reference site, this study establishes a schematized morphodynamic model coupling flow, sediment dynamics and bed level change to explore the processes that govern sediment sorting and bedding phenomena. Model results indicate an overall agreement with field data in terms of tidal current velocities, SSCs, deposition thicknesses and sedimentary structures. Depending on the variation of tidal current strength, sand-dominated layers (SDLs) and mud-dominated layers (MDLs) tend to form during spring and neap tides, respectively. Thinner tidal couplets are developed during daily-scale flood-ebb variations. A larger tidal level variation during a spring-neap tidal cycle, associated with a stronger tidal current variation, favours the formation of SDLs and tidal couplets. A larger boundary sediment supply generally promotes the formation of tidal bedding, though the bedding detail is partially dependent on the SSC composition of different sediment types. Sediment properties, including e.g. grain size and settling velocity, are also found to influence sediment sorting and bedding characteristics. In particular, finer and coarser sediment respond differently to spring and neap tides. During neap tides, relatively small flow velocities favour the deposition of finer sediment, with limited coarser sediment being transported to the upper tidal flat because of the larger settling velocity. During spring tides, larger flow velocities transport more coarser sediment to the upper tidal flat accounting for distinct lamination formation. Model results are qualitatively consistent with field observations, but the role of waves, biological processes and alongshore currents need to be included in further studies to establish a more complete understanding.

# Keywords:

tidal flats; sedimentary structure; sediment sorting; tidal bedding; tidal rhythmite; morphodynamic modelling;

# Introduction

Tidal flats provide valuable ecosystem services and they are commonly found at sediment-rich environments with limited wave action (Kirwan and Megonigal, 2013; Gao, 2019; Murray et al., 2019). As a typical depositional sedimentary environment documented in Reineck and Singh (1973), tidal flats are often built up by multiple sediment types, which display both horizontal sorting and vertical bedding behaviour (Amos, 1995; Friedrichs, 2011; Fan, 2012). Because of the high relevance of sediment dynamics to geomorphological, geological, ecological and environmental changes, understanding sediment sorting and bedding behaviours of tidal flats can benefit interdisciplinary research and serve as the base for sustainable management of coastal wetlands (Mazumder and Arima, 2005; Hopkinson et al., 2019).

The horizontal sorting behaviour is normally characterised by a generally landward fining trend in sediment size on the surface of tidal flats (Figure 1a), and this phenomenon has been widely observed worldwide (Evans, 1965; Amos, 1995; Wang and Ke, 1997; Fan et al., 2013). Using a bed stratigraphy model, Zhou et al. (2015) numerically demonstrated that fine silts and clays tend to distribute on the upper tidal flat while sand accumulates on the middle or lower flat under regular forcing of tides and waves. Increasing wave strength could result in more erosion of fine sediment, leading to a concave profile near the high-water mark. The presence of saltmarshes can stabilize and retain fine sediment even under strong wave action (Spencer et al., 2016; Zhou et al., 2016). Overall, the spatial distribution of sediment grain size is found to be highly linked to the energy distribution of hydrodynamics (Friedrichs, 2011).



Figure 1 (a) Typical zonation of an open-coast tidal flat, modified from Zhou et al. (2016); (b) Sketch of tidal bedding in a sediment core.

The vertical bedding behaviour is typical in tidally-dominated, accretional environments where sediment supply is abundant (Figure 1b). By analysing sediment cores in tidal flats, many field studies have reported the presence of stratigraphic sequences characterised by alternations of sand- and mud-dominated layers (Reineck and Singh, 1973; Allen, 1981; Boersma and Terwindt, 1981; Dalrymple et al., 1991; Nio and Yang, 1991; Shi, 1991; Li et al., 2000; Fan and Li, 2002; Fan, 2012; Choi and Kim, 2016). This phenomenon of tidal bedding is commonly referred to as tidal couplets, tidal bundles, tidal cyclicities or tidal rhythmites in geological literature. Depending on the timescales of tidal variations ranging from daily, semi-lunar to seasonal, tidal bedding may show different vertical structures and sequences of tidal deposits (Nio and Yang, 1991; Mazumder and Arima, 2005; Dalrymple and Choi, 2007; Flemming, 2012). Using the Oosterschelde tidal basin of southwest Netherlands as an example, four types of tidal rhythmites over different timescales were distinguished Nio and Yang (1991): (1) the sand-mud couplets related to flood-ebb cycles, (2) the variation in couplet thickness related to changes in sand transport and mud concentration during diurnal and spring-neap tidal cycles, (3) the variation in the thickness of spring couplets indicating the lunar cycles of high- and low-spring tides, and (4) the variation in rhythmite thickness reflecting longer cycles of tidal variations or seasonal changes in sediment supply.

In contrast to numerous field studies of tidal bedding, laboratory experiments and numerical modelling are rarely reported, except for some sporadic cases (Archer, 1995; Sato et al., 2011; Leonardi et al., 2014). With a circular flume experiment, Sato et al. (2011) found that mud layers tended to form during slack water periods and sand layers during high velocity periods, indicating that different sediment types respond differently to tidal variations. By delineating the spectrum of different tidal regimes from diurnal to semidiurnal tidal systems, a simple, one variable modelling study conducted by Archer (1995) demonstrated that only portions of semi-monthly tidal cycles could be preserved within cyclic tidal rhythmites depending on the temporal variability in tidal current velocities and thresholds for sediment erosion/deposition, and asymmetrical tides played an important role driving the formation of tidal rhythmites. Leonardi et al. (2014) proposed a two-dimensional morphodynamic model to explore the tidal bedding dynamics in distributary mouth bars in delta systems under combined fluvial and tidal forcing. Their findings suggested that a larger tidal amplitude resulted in more distinct laminations and larger differences in successive layers, and moreover, decreasing ratios of concentration and settling velocity between mud and sand promoted an increasing lamination area.

Summarising existing studies on tidal bedding phenomenon, it is found that tidal characteristics, sediment supply conditions and sediment properties are the major factors governing the formation and evolution of tidal rhythmites in tidal flats. Although previous studies have investigated the effects of some individual factors (usually via analyses of field data), there is still a lack of systematic understanding of the mechanisms underlying the stratigraphic architecture in tidal flats. Numerical modelling of intertidal flat sorting and bedding dynamics, which is a useful technique to unravel relevant governing dynamics, has been rarely reported. This study thus sets up a series of explorative numerical models using the tidal flat of Changjiang (Yangtze) Delta as a reference site, aiming to gain more in-depth insight into the magnitude and sequencing of tidal forcing that might need to be considered to explain sediment sorting and bedding dynamics of tidal flats. Specific research objectives include: (1) to unravel the underlying mechanisms that cause sedimentary laminations through detailed and combined analysis of hydrodynamics, sediment transport and morphological change, and (2) to explore the role of tidal characteristics, sediment supply and sediment properties within the stratification process. In doing so, we intend to lay the foundation for future quantitative model development, application, and testing at specific field sites.

# Methods

Based on an open-source morphodynamic model framework (Delft3D), a one-dimensional (1D) profile model is considered using the Nanhui tidal flat of Changjiang Delta as a reference site. The study site and the morphodynamic model are introduced below.

## Study site

The Nanhui tidal flat of interest is located on the south flank of the Changjiang Delta which has been prograding because of fluvial sediment supply (Figure 2a-e). From 1950 to 1994, the coastline of Nanhui tidal flat prograded with an average rate of 41.6 m/year (Fan et al., 2002). As documented in Fan et al. (2017), large scale land reclamations have been continuously carried out since 2000 for increasing socioeconomical development in Shanghai, and most of the tidal flats that existed at that time have been lost since then (Figure 2). Before recent land reclamation projects, detailed bed level observations of tidal rhythmic depositions were conducted on a cross-shore profile of this tidal flat from May 24 to July 12, 1999 by Fan et al. (2001), providing a valuable dataset for model validation and comparison (Figure 2c). During the measuring period, the average width of the tidal flat was approximately 3.3 km with an average slope of about 1 ‰. Based on the ground elevation measurement, Fan et al. (2001) also estimated the bed slopes of different sections along the profile. The vegetated flat was bounded by seawalls and occupied by salt marshes with a slope of about 1.5 ‰, and the upper and lower flats were unvegetated with a gentler slope of about 0.4 ‰ and 0.8 ‰, respectively (Figure 2f). The vegetated and upper tidal flat were generally characterised by clayey silt, the lower flats by sandy silt and silty sand, respectively (Fan et al., 2006).

The average semidiurnal tidal range at the Changjiang Estuary mouth is about 2.6 m with a spring tidal range of 4.5 m. Tidal flow shows a flood-dominated characteristic with a faster flood, resulting in a landward sediment transport (Li, 1991). On the upper flat, the maximum flood velocities were found to vary from 0.21 m/s during neap tides to 0.35 m/s during spring tides, while maximum ebb velocities were about 0.13 m/s during both neap and spring tides (Li, 1991; Fan and Li, 2002). The yearly average wave height measured at a nearby observation station in Hangzhou Bay (Tanxu station, about 25 km from the shore) is about 0.4 m with a maximum of 4 m during storms (Wang and Eisma, 1990). Waves on the tidal flat were generally low and dissipated across the broad tidal flat during calm weather. Storms and typhoons were found to result in the formation of SDLs and significantly decrease the preservation potential of tidal bedding (Li et al., 2000). The suspended sediment concentration (SSC) shows a strong temporal variation (Chen et al., 2006) and could reach 4.36 kg/m3 at the flood spring tide, while during neap conditions, the SSC remained as high as 1.72 kg/m3 during flood and 0.79 kg/m3 during the ebb. The yearly average SSC is around 1.45 kg/m3 at the study site.

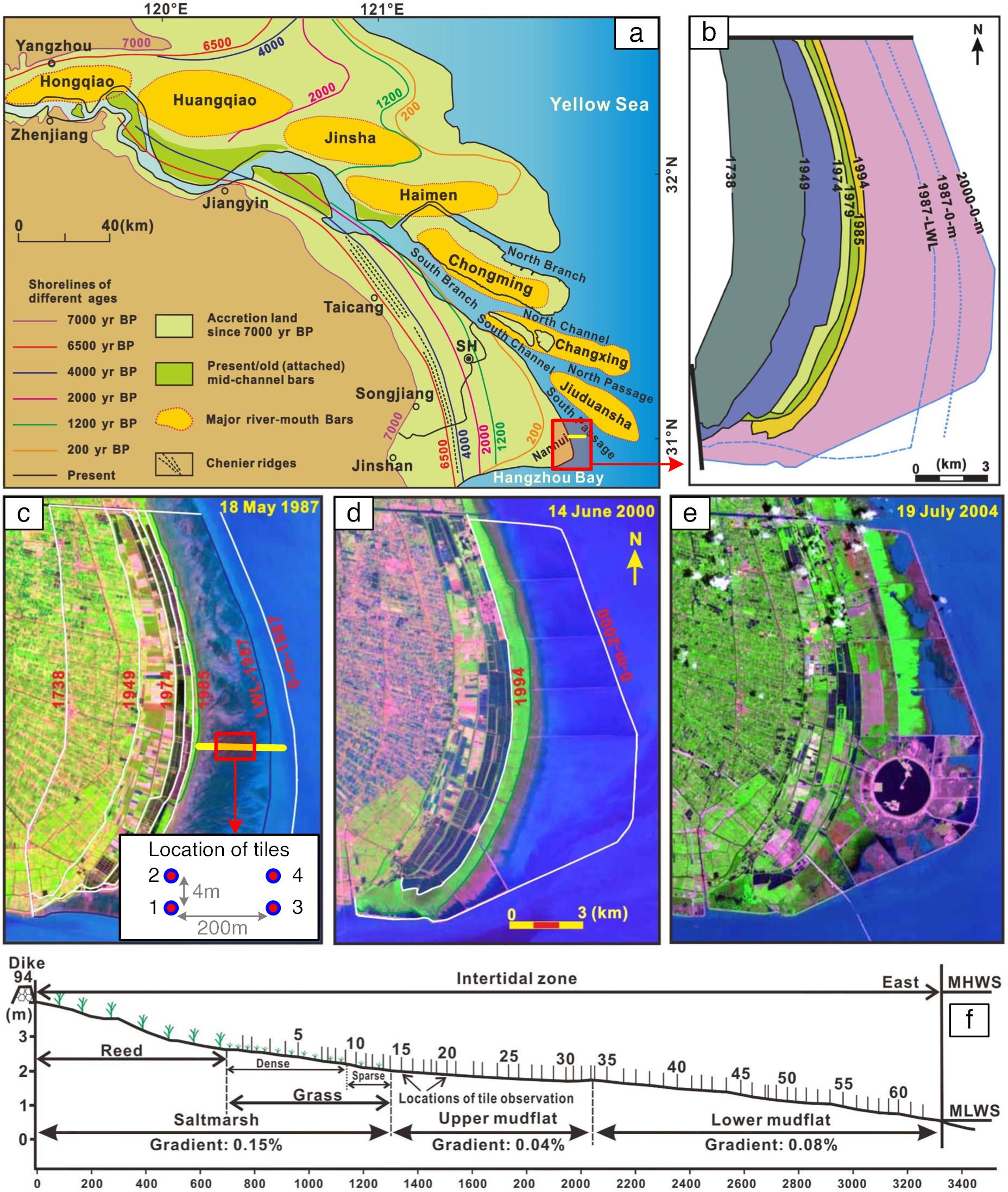


Figure 2 Location of the Changjiang Delta (a), location of the study site on the Nanhui tidal flats and their historical evolution (b-e), and bed elevation of the profile (f). This figure is modified from Fan et al. (2017)

Four thin plastic tiles (with a length of 0.4 m, a width of 0.4 m and a thickness of 0.005 m) were established on the upper tidal flat to record the deposition of sediments over about 3 spring-neap tidal cycles (Fan and Li, 2002). Tiles 1, 2 and 3, 4 were placed near stake 15 and 20, respectively (Figure 2c, f). Since the tiles within each of the pairs 1-2 and 3-4 were at the same elevation (within a short cross-shore distance of one another), we calculated the average values of the observed velocity, SSC and accumulative deposition between the tiles of the same elevation for validation and comparison with model results. The cross-shore location of tiles 1/2 and 3/4 are indicated by T1 and T3 in Figure 3. The measured daily sediment deposition at T1 and T3 varied from 0.5 to 25 mm with silt being the major fraction. The average thickness of couplets deposited during spring and neap tides were respectively about 4.5 mm and 3.5 mm. The observed field data of Fan and Li (2002) are used to set up the morphodynamic model in this study.

## Model description and configuration

An open-source morphodynamic model (Delft3D), which has been extensively described in previous studies (Lesser et al., 2004; van der Wegen et al., 2011; Zhou et al., 2014), is used here and hence is only briefly introduced. The model consists of several coupled modules describing hydrodynamics, sediment transport and stratigraphy, and bed level change.

The flow module solves the shallow water equations resulting in the flow field (i.e. velocities and water levels), which is then fed into the calculation of sediment transport and morphological change. The sediment transport module deals with both cohesive and non-cohesive sediments. Cohesive sediment is considered as suspended load which is evaluated using the sediment advection-diffusion equation and its erosion/deposition is treated following the classic Partheniades–Krone formulations (Partheniades, 1965). Non-cohesive sediment transport is calculated using the formulations of van Rijn and Walstra (2004), in which both bed load and suspended load are considered.

The morphodynamic model includes a bed stratigraphy module which divides the erodible bed into multiple layers and tracks different sediment fractions in each layer over time (Leonardi et al., 2014; Zhou et al., 2015; Zhou et al., 2016; Deltares, 2020). For practical treatment, the bed layers include an uppermost active layer, a few intermediate layers and a lowermost base layer. When erosion occurs, the amount of erosion during one hydrodynamic time step is limited to the sediment that is available in the active layer. The thickness of the active layer (δ) is maintained as a constant by a replenish procedure at the beginning of every time step: if the layer thickness produced by this procedure is larger than δ, the excess sediment is moved to the second layer; if its thickness is smaller than δ, sediment in the layers below is supplied to the active layer. The amount of different sediment fractions (e.g. sand or mud) of the contributing layer that move to the receiving layer depends on the relative percentage of sediment fractions in the contributing layer. The above procedure is repeated during the entire simulation and hence the sediment composition and thickness of each layer is updated. According to Fan and Li (2002), the observed thickness of tidal couplets ranges from 0.5 mm to 20 mm, so the thickness of each layer is set to the order of ~mm in order to capture the small tidal couplets. A sensitivity analysis has also been performed and it shows that using an active layer thickness of 10 mm, 5 mm and 1 mm results in qualitatively comparable sediment sorting and bedding structures, but a larger active layer thickness cannot ensure a detailed representation of the fine bedding architecture observed in natural tidal flat systems. To better reflect the tidal bedding features, a small active layer thickness of 1 mm is therefore used. Model results indicate that the amount of sediment erosion at one hydrodynamic time step (0.5 min) is found to be always smaller than 1 mm for the simulations undertaken with tidal forcing, suggesting that an active layer thickness of 1 mm is reasonable in this study. However, it should be noted that the thickness of active layer should be set a larger value when hydrodynamics are strong (e.g. occurrence of storms). Therefore, the choice of the active layer thickness is a trade-off between physical representation needs and numerical limitations, which should be carefully determined via sensitivity analysis. The total number of bed layers is set to a large number of 402 so as to show the detailed bedding characteristics.

Following the field study of Fan and Li (2002) who conducted detailed measurements along a cross-shore profile (Figure 2f), we set up a one-dimensional morphodynamic model using comparable profile shapes (in terms of bed elevations and slopes). Consistent with field observation, the initial bathymetry of the profile consists of 3 linear sections: a vegetated flat with a slope of 1.5 ‰, an upper flat of 0.4 ‰ and a lower flat of 0.8 ‰ (Figure 3). Three types of sediments are considered: fine sand, silt and clay. Silt is treated as non-cohesive sediment in this study using the sediment transport formula of van Rijn and Walstra (2004). Sand transport initiation and landward movement requires greater flow speeds that of silt and clay because of its larger critical shear stress for erosion and larger settling velocity. The settling velocity and the critical shear stress for erosion of sand and silt are dependent on their mean grain size. For clay, the user needs to specify the values of the settling velocity and the critical shear stress for erosion. To make the model as transparent as possible, the initial bed is assumed to be covered with a sand layer of 2 m, mimicking a depositional environment for silt and clay. For simplicity, some sediment processes such as the interaction between cohesive and non-cohesive sediments, consolidation and bioturbation are not considered. Five observation points T1, T3, P1, P2 and P3 are established at the cross-shore distance of approximately 1400 m, 1600 m, 2000 m, 3200 m and 3800 m, respectively. The first two observation points (T1 and T3) are located at the same position as field tiles 1 and 3 so that direct comparisons can be made.



Figure 3 Schematised initial model bathymetry based on Fan and Li (2002), see also Figure 2f. Five observation points are selected for subsequent analyses: two observation points corresponding to the field tiles in Fan and Li (2002) on the middle flat (indicated by T1 and T3) and three additional observation points (indicated by P1, P2 and P3). Tidal levels of mean high water spring and mean low water spring are indicated by MHWS and MLWS, respectively.

The tidal boundary is imposed at the water depth of 10 m and forced by the superposition of three major tidal constituents (i.e. M2, S2 and M4). The amplitudes of other tidal constituents are comparatively small and hence not considered for simplicity (Chu et al. 2015). For the reference case, a spring tidal range of about 4.5 m is considered following tidal observation data in the study site. Consistent to the field observation documented in Fan and Li (2002), model simulations started from the neap tide and covered 3 entire spring-neap tidal cycles of approximately 50 days. Fan and Li (2002) suggested that waves on this tidal flat were low and considerably dissipated during shoreward propagation, so waves are not considered in this study. In fact, waves can play a significant role in tidal flat sorting and bedding dynamics depending on tidal modulation. The role of strong waves during storm events (Fan et al., 2006; Friedrichs, 2011) deserves a full and detailed investigation through separate research and is not the focus of this study.

In total, 14 simulation cases are conducted and shown in Table 1. The values of model parameters for the reference Case 1 are mostly chosen based on field observation documented in Fan and Li (2002). In order to investigate the role of different parameters, 13 other simulation cases are designed by varying the parameters of tidal constituents, boundary SSCs and sediment properties. Some other model parameters are chosen based on sensitivity tests and existing literature (Fan and Li, 2002; Leonardi et al., 2014; Zhou et al., 2014; Zhou et al., 2015; Zhou et al., 2016; Zhou et al., 2016; Deltares, 2020), including, for example, hydrodynamic time step (0.5 min), horizontal eddy viscosity (1 m2s-1), horizontal eddy diffusivity (10 m2s-1), Chézy frictional coefficient (65 m1/2s-1), mud erosion parameter (10-4 kgm2s-1) and morphological factor (1). The critical shear stress for deposition is set to a very large value (1000 Pa), following the concept of continuous deposition (Winterwerp, 2007; Leonardi et al., 2014).

Table 1 Overview of designed simulations. The parameters *a*M2, *a*S2 and *a*M4 represent the tidal amplitude of M2, S2 and M4 constituents. The parameters , and represent the boundary SSC of clay, silt and sand. The rest parameters , , and represent mean grain size of silt and sand, the critical erosion shear stress and settling velocity of clay. Case 1 is the reference case and the shaded parameters of the other cases are varied based the reference case.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Case ID | Tidal amplitude | | | Boundary sediment concentration | | | Sediment properties | | | |
| *a*M2 | *a*S2 | *a*M4 |  |  |  |  |  |  |  |
| (m) | | | (kg/m3) | | | (mm) | | (Pa) | (mm/s) |
| R1 | 1.75 | 0.5 | 0 | 2 | 4 | 1 | 0.02 | 0.08 | 0.1 | 0.025 |
| R2 | 1.83 | 0 | 0 | 2 | 4 | 1 | 0.02 | 0.08 | 0.1 | 0.025 |
| R3 | 1.8 | 0.3 | 0 | 2 | 4 | 1 | 0.02 | 0.08 | 0.1 | 0.025 |
| R4 | 1.65 | 0.75 | 0 | 2 | 4 | 1 | 0.02 | 0.08 | 0.1 | 0.025 |
| R5 | 1.75 | 0.5 | 0.2 | 2 | 4 | 1 | 0.02 | 0.08 | 0.1 | 0.025 |
| R6 | 1.83 | 0 | 0.2 | 2 | 4 | 1 | 0.02 | 0.08 | 0.1 | 0.025 |
| R7 | 1.75 | 0.5 | 0 | 1.5 | 3 | 0.75 | 0.02 | 0.08 | 0.1 | 0.025 |
| R8 | 1.75 | 0.5 | 0 | 1 | 2 | 0.5 | 0.02 | 0.08 | 0.1 | 0.025 |
| R9 | 1.75 | 0.5 | 0 | 2 | 2 | 1 | 0.02 | 0.08 | 0.1 | 0.025 |
| R10 | 1.75 | 0.5 | 0 | 2 | 1 | 1 | 0.02 | 0.08 | 0.1 | 0.025 |
| R11 | 1.75 | 0.5 | 0 | 2 | 4 | 1 | 0.05 | 0.08 | 0.1 | 0.025 |
| R12 | 1.75 | 0.5 | 0 | 2 | 4 | 1 | 0.02 | 0.065 | 0.1 | 0.025 |
| R13 | 1.75 | 0.5 | 0 | 2 | 4 | 1 | 0.02 | 0.08 | 0.3 | 0.025 |
| R14 | 1.75 | 0.5 | 0 | 2 | 4 | 1 | 0.02 | 0.08 | 0.1 | 0.05 |

# Results

## Tidal hydrodynamics

Tidal currents serve as the major factor governing the sediment dynamics and hence shaping up the morphology of tidal flats (Friedrichs, 2011). Using the reference case R1 as an example, we hereafter present some model results of tidal hydrodynamics. Model calibration is conducted using the measured hydrodynamic data (e.g. tidal velocities and SSCs) collected by Li (1991). On the basis of a correctly described hydrodynamics, the measured sediment accumulation presented in Fan and Li (2002) is considered for model validation.

Figure 4 shows the temporal variation of tidal hydrodynamics and associated SSCs at three observation points (P3, P1 and T3) over a spring-neap tidal cycle. Since T3 and P1 are located between MHWS and MLWS, there is a period of tidal flat emergence in contrast to the entire submergence of P3 which is located below MLWS (Figure 4a). The magnitude of tidal currents shows a decreasing trend and tidal asymmetry of peak velocities becomes more evident during tidal propagation toward the shore. Comparable to field observations (Li, 1991), the peak tidal current velocities reach about 0.4~0.5 m/s during the spring period, while 0.2~0.3 m/s during the ebb period (Figure 4b).

The variation of SSC values generally follows the same trend as tidal velocities (Figure 4c), peaking at spring tide with a maximum SSC of approximately 3 kg/m3 which is consistent with field observations (Li, 1991; Fan and Li, 2002). The peak SSCs of observation points P3, P1 and T3 are all within 2.8-2.9 kg/m3 during the spring period but differ during the neap period. The SSC at the landward point T3 during the neap tide ranges between 0.5 and 1 kg/m3, which is roughly a half of that at P3. Focusing on P1, it is also worth pointing out that clay, silt and sand behave differently under the same hydrodynamic conditions. Compared to silt and clay, the SSC of sand is much smaller even during the spring tide because of its larger critical shear stress for erosion and settling velocity. Silt is mostly suspended during the spring tide with a peak SSC of about 1 kg/m3. The temporal and spatial difference in SSC for clay, silt and sand serves as one of the fundamental reasons for their different sorting and bedding behaviours as described in the following sections. Overall, the simulated tidal hydrodynamics and SSCs are generally in agreement with field observations.



Figure 4 Temporal variation of water level (η), velocity (u) and suspended sediment concentration (SSC) at observation points P3, P1 and T3 during a spring-neap tidal cycle of the reference case R1.

## Bed level and sedimentary features

Because of the abundant sediment supply, the simulated bed level evolution shows a gradually accretional behaviour during 3 spring-neap tidal cycles (Figure 5). The amount of sediment deposition differs spatially. The deposition thicknesses of the two observation points T1 and T3 are roughly 0.15 m and 0.13 m, while roughly 0.15 and 0.4 m for P2 and P3, respectively. Among the five observation points, P1 receives the least deposition of about 0.05 m because it is near the inflexion point of the initial bathymetry. According to the measured data in Fan and Li (2002), the average deposition thickness of tiles 1-4 during field observation is approximately 0.2 m (Figure 2c), being comparable to the numerical modelling result. The large deposition near the seaside domain is mainly because of the considerable settling of fine sediment induced by high boundary SSC, which will be further discussed in the following sections.

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Figure 5 Evolution of bed levels after 1, 2 and 3 spring-neap cycles (indicated by ‘SN’ in the legend) and cumulative deposition/erosion (Δz) of the reference case R1.

The simulated detailed bed stratigraphy during the observation period is shown in Figure 6. Near the landward end of the transect, the dominant sediment type is clay which then transits to silt toward the lower flat (Figure 6a-b), showing an overall landward fining phenomenon (Amos, 1995; Fan, 2012; Zhou et al., 2015). Sand, initially composing the bed, is mainly distributed at the bottom of the bed, indicating that sand transport is comparably much smaller than that of clay and silt (Figure 6c). In fact, the sand fraction in the upper layers is barely noticeable except at the observation point P1 where sediment deposition is small compared to the other observation points (Figure 5).

During the simulated 3 spring-neap tidal cycles, a clear bed stratigraphy characterised by 3 couples of alternate layering structures is formed, particularly on the upper and lower flats where observation points T1, T3, P2 and P3 are located (Figure 6a-b). Each of the layer structures is formed during one of the spring-neap tidal cycles. Because of the spatially different depositions, the thickness of each layer at different observation points differs. A scrutiny of the detailed layering couplets is shown by Figure 7. The initial sediment deposit at the bottom of the layering structures is dominated by clay at the observation points T1 and T3 (Figure 7a), because the model is started with a neap tide during which flow velocities are too small to transport silt and sand but favour fine sediment deposition (Figure 4). During the spring tidal phase, both clay and silt are transported to the upper tidal flat but the amount of silt transport is comparably smaller as it settles more rapidly. Closer to the seaward end of the transect, a larger deposition is observed in layers with the dominance of silt at the observation points P2 and P3 (Figure 7b). The individual thickness of the three alternate layer structures is similar at T1, T3 and P2. In contrast, the layer thickness at P1 and P3 varies considerably during each spring-neap tidal cycle. For example, the thickness of the three clay-dominated layers forming during neap tide at P1 increases from the bottom to the top (Figure 7a), indicating that the bed level evolves to a state favouring clay deposition. It is also worth pointing out that a number of thin couplets form at the daily timescale of flood and ebb, which is also commonly observed in field observations (Dalrymple et al., 1991; Shi, 1991; Li et al., 2000; Fan et al., 2002; Fan and Li, 2002). A detailed interpretation of the layering phenomenon is provided in the following section.

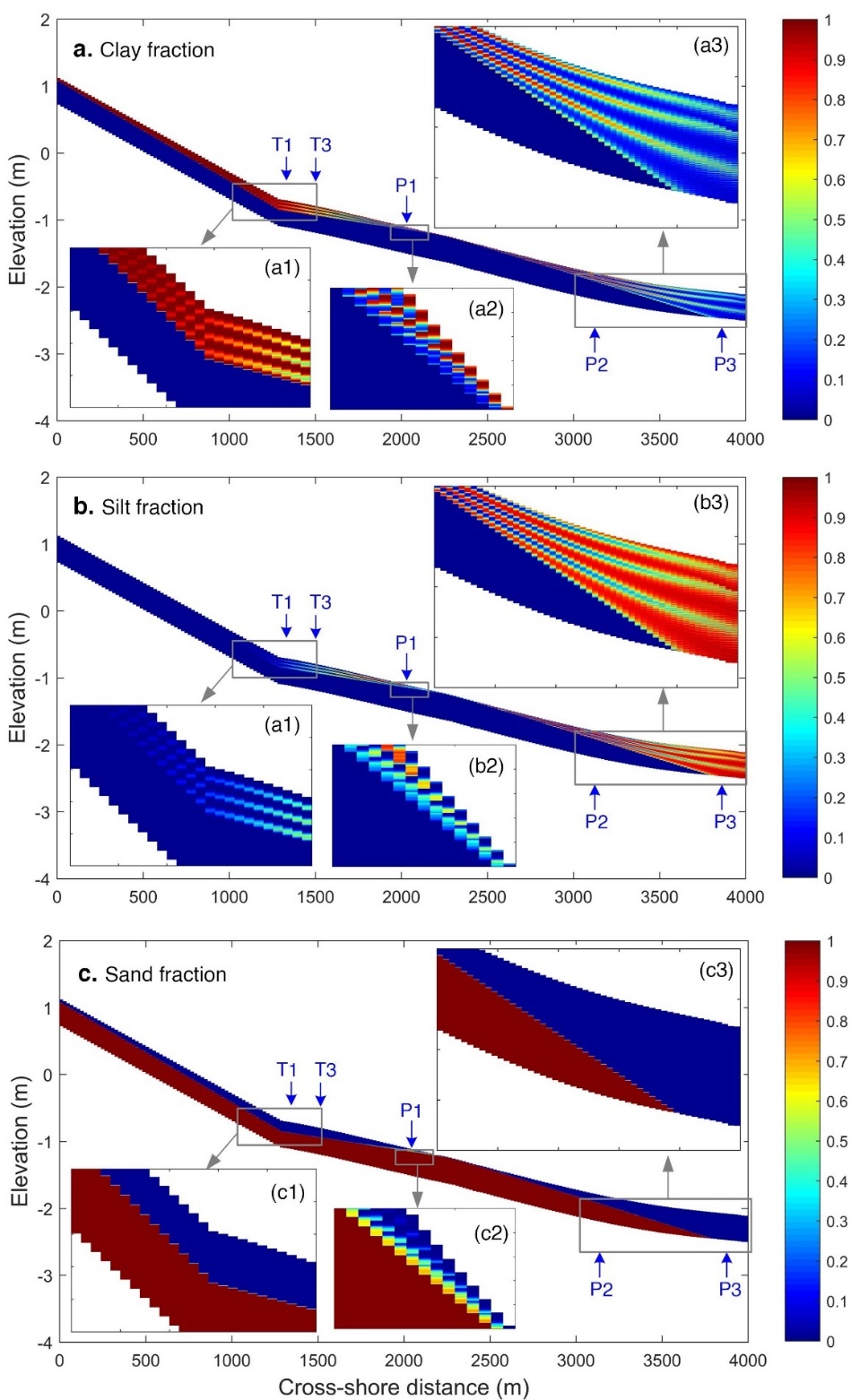


Figure 6 Simulated sediment composition in the bed of the reference case R1.: (a) clay fraction, (b) silt fraction and (c) sand fraction. Colorbar indicates the volume fraction of sediment.

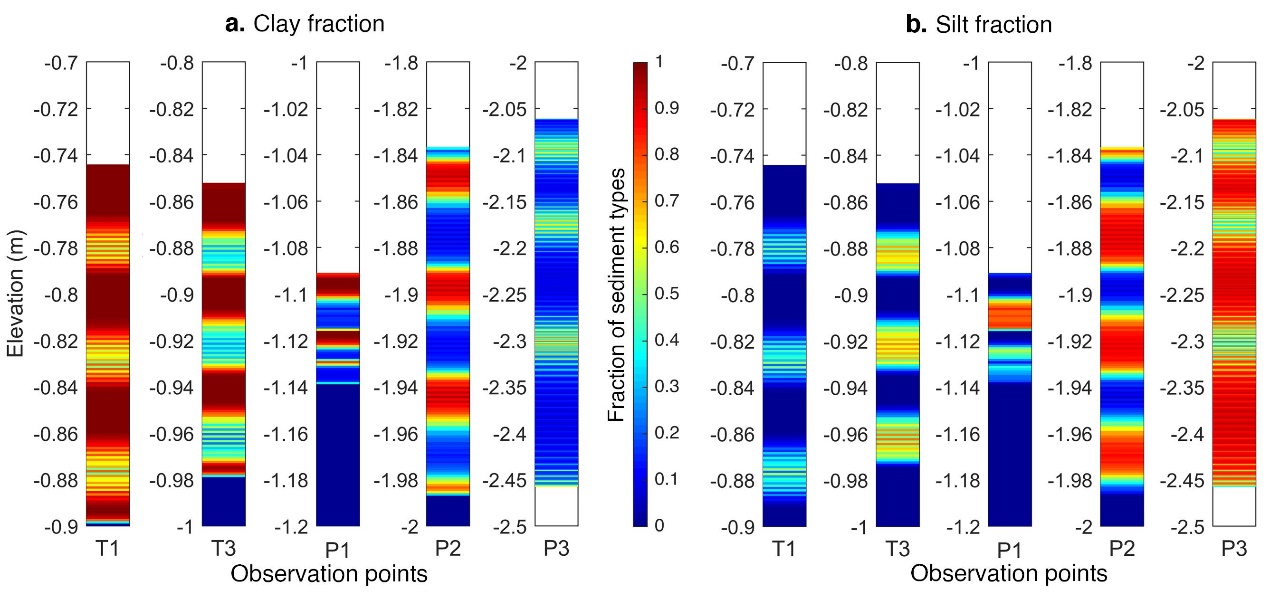


Figure 7 Spatial tidal bedding of different sediment types (clay and silt) at different observation points of the reference case R1.

## Tidal bedding dynamics

A detailed bed stratigraphy, with the exact volume fraction of clay, silt and sand at different observation points, is shown in Figure 8. Consistent with previous results, the clay fraction is high in the bed layers of the upper tidal flat (see T1). The silt fraction is smaller than 40% even in the layer formed during the spring tide periods. As discussed in Fan and Li (2002), the dominance of clay deposition on the upper tidal flats makes it hard to differentiate the daily-scale thin tidal couplets formed during flood-ebb variations. A relatively clear formation of tidal couplets is present mainly during the spring tide periods. Overall, during a spring-neap tidal cycle at T1, approximately 23 thin tidal couplets are formed with an average thickness of about 1 mm. Since T3 is close to T1, the tidal bedding phenomenon is similar though silt dominated layers start to occur. For simplification of layer descriptions, Fan et al. (2002) defined a coarser layer of sand and/or silt as “sand-dominated layer” (SDL) and a finer layer of clay and/or silt as “mud-dominated layer” (MDL). Therefore, it should be noted that the terms SDL and MDL are defined in a relative sense by comparing the grain sizes of alternate neighbouring layers. At site T1, there are only MDLs as the volume fraction of silt in layers is always smaller than 0.5. There are alternate SDLs and MDLs at T3 because the silt fraction can be larger than 0.5 during spring tide periods. The number of tidal couplets at T3 is roughly 15 during a spring-neap tidal cycle. The situation at P1 is different, as the thickness of the three individual SDLs (or MDLs) differs considerably and sand transport appears to be much larger than that at other sites. Moving more seaward at sites P2 and P3, more tidal couplets are formed, even during the neap tide (when MDLs dominate). Approximately 34 tidal couplets are formed during a spring-neap tidal cycle at P2, and the number of couplets increases to about 54 at P3 with an average couplet thickness of about 3 mm.

According to previous studies, the theoretical number of tidal couplets forming over a spring-neap tidal cycle can reach up to 52-58 on semi-diurnal coasts (Archer and Johnson, 1997; Fan and Li, 2002). However, the number of tidal couplets observed in the field during a spring-neap cycle was about 23-28, preserving only about 40% of the theoretical number at the Nanhui tidal flat (Fan and Li, 2002). These studies also found that the thickness of couplets progressively increases from neap to spring tides, which is consistent with model results at site P2 (Figure 8). Besides, model results indicate that the preserved number of tidal couplets differs spatially. At the seaward sites P2 and P3, more tidal couplets are formed because of a larger deposition close to the boundary. The number of couplets reaches the theoretical maximum value at P3, indicating that this site is dominated by deposition rather than erosion and hence favouring the preservation of tidal couplets. It should be noted that P3 is quite close to the model boundary and the amount of sediment deposition may be overestimated.



Figure 8 Vertical volume fraction distribution of different sediment types at different observation points of the reference case R1. The capital letters “S” and “N” denote spring and neap periods respectively. Note that the vertical scale of P3 plot is different from the other plots.

At other sites of the upper tidal flat, the couplets formed during the flood tide may be eroded during the ebb, which is one of the reasons that the number of tidal couplets is smaller than the theoretical maximum (Fan and Li, 2002). To gain more in-depth insight, the temporal variation of sediment composition in the upmost layer during a spring-neap tidal cycle is analysed against the temporal variation of the cumulative erosion or deposition (Δz, Figure 9). The silt fraction in the active layer is found to increase gradually from neap to spring tides. During neap tide (e.g. from 0 to 4 days), the top active layer at T3 is nearly all filled by clay deposit, which contributes to the bed level increase. During spring tide (e.g. from 6 to 10 days), the silt fraction becomes more active and its volume content can reach up to about 0.7 in the active layer at T3. Noticeably, the bed level change during the spring tide is more rapid than that during the neap, which is mostly because of the additional silt deposition. At the daily timescale, the bed level increases during the flood period while it decreases slightly during the ebb. The daily variation in bed level change between the flood and the ebb is more pronounced at P1, as Δz declines from, roughly, day 4 to day 8. The deposited sediment is partially eroded away and the vertical sediment mixing is strong, so the bed stratigraphy is not well developed at P1. The sand fraction plays a more important role at P1 than at the other sites. In contrast to T3 and P1, at P3, depending on the tidal amplitude, a large fraction of the active layer can be composed by either silt (spring tides) or clay (neap tides). Since P3 is close to the boundary, the suspended silt can be transported to a certain distance without settling down even during the neap tide, hence favouring the formation of tidal couplets.



Figure 9 Temporal variation of sediment volume fraction in the top active layer and the cumulative erosion/deposition (Δz) during the second spring-neap tidal cycle at observation points T3, P1 and P3 of the reference case R1.

# Discussion

## Role of tidal constituents

Insights gained from field studies along with the above model results suggest that tidal bedding features are largely determined by the variation of tidal current velocities that are primarily governed by the tidal regime (Boersma and Terwindt, 1981; Archer, 1995). To investigate the effect of tidal regime, four simulation cases (R1-R4, Table 1) are designed by varying the ratio of tidal amplitudes between tidal constituents S2 and M2 (indicated by S2/M2). The tidal energy during a spring-neap cycle of the four cases is kept the same so that they are comparable. The vertical distribution of sediment volume fraction for different cases is shown in Figure 10. With a larger S2/M2 (and hence a larger variation of tidal level), the development of tidal couplets is more pronounced, and the formed SDLs are thicker. Therefore, it suggests that a larger change in tidal levels (and hence flow velocities) favours the formation of tidal couplets (Figure 10e-f). It is worth noting that there is no evident bed stratigraphy of SDLs and MDLs in the M2-only case R2 (S2/M2 = 0), though insignificant tidal couplets characterised by the zigzag curves of sediment volume fraction (Figure 10a) tend to form during the flood-ebb variations.



Figure 10 Vertical volume fraction distribution of different sediment types at observation point T3 for increasing ratio of amplitude between S2 and M2 tidal constitutes for cases R1-R4 (a-d). The variation of water level and velocity during a spring-neap tidal cycle for cases R2 and R4 (e-f). The capital letters “S” and “N” denote spring and neap periods respectively. The light blue bar shows an example of the spring tidal period.

As tides propagate toward the shore, tidal wave is distorted due to bed friction and tidal asymmetry occurs (Zhou et al., 2018). Flood-dominance, characterised by a larger maximum flood velocity (or shorter flood duration) than that of the ebb, is quite common at the nearshore (Friedrichs and Aubrey, 1988). Tidal asymmetry plays a significant role on net sediment transport of coastal and estuarine systems. Flood dominance is found to favour net landward sediment transport and hence promote deposition, which can potentially affect tidal bedding dynamics (Boersma and Terwindt, 1981; Archer, 1995; Archer and Johnson, 1997). By adding a boundary M4 tidal constituent to simulation cases R1 and R2, the tidal bedding features of flood-dominated scenario (R5 and R6, Table 1) are shown in Figure 11. It is apparent that the additional M4 constituent can considerably promote not only sediment deposition but also the development of tidal couplets. Comparing cases R1 and R5 at sites T3 and P1, it is observed that more and thicker tidal couplets are formed. Besides, it seems that the addition of M4 constituent tends to enhance the development of SDLs. However, adding a M4 constituent to case R2 (the M2-only case) does not fundamentally change the bedding structure (see Figure 10a and Figure 11c), but more and clearer tidal couplets are developed during flood-ebb variations. It is worth noting that different sediment types play different roles: clay and silt mostly play an active role while sand at most locations plays a passive role on tidal couplet formation because sand particles are more difficult to be mobilised and settle down more rapidly. Therefore, sand particles, either supplied from the boundary or mobilised from the bed, travel much shorter distances with tidal currents, which is the reason for minor or no sand fraction at site T3 (Figure 11a-c). At site P1, sand becomes more active because of a higher flow velocity, resulting in a larger sand fraction in the bed layers (Figure 11d-f). Overall, model results indicate that flood-dominance, which is typical on tidal flats, favours the formation of tidal couplets.



Figure 11 Vertical volume fraction distribution of different sediment types in cases R1, R5 and R6. The capital letters “S” and “N” denote spring and neap periods respectively. Subplots a-c share the same y-axis and d-f the same y-axis.

## Role of sediment supply and sediment properties

Sediment supply has been found to play a significant role on tidal flat sorting dynamics and hence morphodynamics (Mariotti and Fagherazzi, 2010; Friedrichs, 2011). By varying the boundary SSCs of clay, silt and sand (, and ), five simulation cases are designed, and their modelling results are compared in Figure 12. For 3 cases (R1, R7 and R8, Table 1), the ratio between , and is fixed to 2:4:1, while their overall SSCs decrease from R1, R7 to R8. The boundary total SSC of R7 and R8 is respectively 3/4 and 1/2 of R1, which greatly determines accumulative sediment deposition (Δz). In agreement with the ratio between the boundary SSCs, the value of Δz for cases R1, R7 and R8 is approximately 13 cm, 10 cm and 7 cm, respectively (Figure 12a-c). Though Δz differs, the overall bedding structure of SDLs and MDLs is similar. It is however worth noting that a larger boundary SSC favours the formation of tidal couplets. By comparing cases R1 with R9 and R10, it is found that reducing the boundary SSC of silt does not significantly affect the overall sediment deposition, because clay is the dominant sediment type building up the upper tidal flat at T3 (Figure 12d-e). However, it is noted that the SDLs of cases R9-R10 are not as well developed as R1.



Figure 12 Vertical volume fraction distribution of different sediment types at observation point T3 for different sediment supplies. Subplot (a) is the reference case and other subplots show the results of cases R7-R10, see Table 1 for the definition of the parameters.

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Figure 13 Vertical volume fraction distribution of different sediment types at observation point T3 for different sediment properties. Subplot (a) is the reference case and other subplots show the results by varying only one parameter, see Table 1 for the definition of the parameters.

Apart from sediment supply, sediment properties are also found to play an important role on the development of bed stratigraphy and a few cases are designed (R11-R14, Table 1). Increasing the mean grain size of silt (case R11) can reduce sediment deposition at T3 and no obvious tidal couplets are formed compared to R1 (Figure 13a-b), because a larger grain size results in a larger settling velocity hampering landward silt transport to the upper flat. Decreasing the mean grain size of sand (case R12) does not affect the overall bedding structure, but can slightly increase the sand volume fraction in the first SDL during the spring tide (Figure 13c). Increasing the critical shear stress for clay erosion does not seem to greatly affect the cumulative deposition, but can play a negative effect on the formation of tidal couplets (Figure 13d). This is because the deposited clay at T3 is more difficult to be initiated and put back into water column in suspension, and hence the bed layers are more prone to be filled by clay. Increasing the settling velocity of clay (R14) favours sediment deposition and the development of tidal couplets (Figure 13e), though SDLs are not as developed as R1 because clay can occupy bed layers more rapidly. Finally, it is also found that clay and silt respond differently to spring and neap tides. During neap tides, flow velocities are relatively small favouring the deposition of clay, whilst silt transport to the upper tidal flat is limited due to its higher settling velocity. During spring tides, flow velocities are larger so that more silt can be transported to the upper tidal flat accounting for more fraction in bed layers.

## Model capabilities and limitations

In spite of the relative simplicity, the present model is among one of the first numerical attempts that capture sediment sorting and bedding phenomena on tidal flats successfully, with a qualitative agreement between model results and field observation. This suggests that this model is well suited to providing a basis for future explorative analysis of tidal flat sediment dynamics. Furthermore, we have shown that, by applying models such as this, it is possible to gain a mechanistic understanding of the underlying dynamics governing sediment sorting and bedding dynamics on tidal flats. Beyond the phenomenon and insight gained from field data, some hidden physical mechanisms can be unravelled by the numerical model. For example, it is found that an increasing ratio of tidal amplitude between S2 and M2 constituents (i.e. increasing temporal variation of tidal levels) favours the formation of SDLs and tidal couplets.

It is, however, worth pointing out that tidal flat sediment dynamics are governed by a variety of processes operating over different temporal and spatial scales, e.g. tides, waves, riverine flows, biological activities, sea level variations and storms. In order to facilitate an easier interpretation of model results, some simplifications and assumptions have been made in this study to limit the number of processes in consideration. It is also worth discussing the role of some neglected processes which can be considered for further research, as follows.

(1) Waves, and storms in particular, may play a significant role on sediment sorting and bedding dynamics (Fan et al., 2004; Fan et al., 2006; Eichentopf et al., 2019). Depending on the modulation of tidal levels, the influence of wind waves and storm generated currents may be different. Because of the stronger bed shear stresses induced by wind waves and storm-induced currents, coarser sediment can be mobilised and brought shoreward and form clear thicker SDLs. Several studies have found that waves can destroy tidal couplets which is one of the reasons that the number of tidal couplets developed during a spring-neap tidal cycle is unlikely to reach the theoretical maximum (Li et al., 2000; Fan and Li, 2002; Fan et al., 2004; Fan et al., 2006; Fan, 2012). Further research effort should be made to comprehensively address the role of waves and storms on sediment sorting and bedding dynamics. It is worth noting that the value of the active layer thickness with waves included should be much larger than the value used in the present study, because the wave-induced sediment suspension and mixing on tidal flats is more significant than tides alone.

(2) The effects of biological processes, e.g. salt-tolerant vegetation, benthic animals and micro-organisms, are not accounted for in this study while many recent studies suggest their importance in sediment and tidal flat dynamics (Chen et al., 2017; Chen et al., 2020; Finotello et al., 2020; Huang et al., 2020). Biological processes can be either stabilizers or de-stabilizers of bed sediment, and their biological behaviours and life cycles can greatly affect sediment grain size distribution not only on the surface of the bed but also inside the bed. Further studies should be considered to explore the importance of how biological processes can lead to longer-term change by causing ‘system switching’ (i.e. the retention, rather than accretion and removal of layers) over a prolonged period of time (Murray et al., 2008; Fagherazzi et al., 2013).

(3) Because of the 1D model configuration, the role of alongshore tidal currents is not considered in this study. Wang et al. (2019) demonstrated that strong alongshore currents can interact with cross-shore currents and promote the development of the lower sandy flat. Besides, the addition of alongshore currents may cause larger bed shear stress, promoting the initiation and transport of sand. Therefore, in contrast to the model results presented here, coarser sediment could, play a more active role in tidal bedding dynamics if alongshore tidal currents are taken into account.

# Conclusions

A novel application of a morphological model, in conjunction with data from the Nanhui tidal flat on the Changjiang Delta, China, has led to a deeper understanding of the mechanisms underlying sediment sorting and bedding on tidal flats. Model results of tidal velocities, SSCs, sediment deposition and tidal bedding features show a qualitative agreement with field observations. The SDLs tend to form during spring tide phases when tidal current velocities are relatively larger while the MDLs develop during the neap tide phases. Daily-scale tidal couplets resulting from flood-ebb variations are also reproduced by the model. Due to possible erosion of the thinner deposited layers, the number of tidal couplets formed during a spring-neap tidal cycle is commonly less than the theoretical maximum value, especially on the upper tidal flat.

The effects of tidal regime, sediment supply and sediment properties are also explored by designing a few numerical experiments. Model results suggest that a larger variation in tidal levels (and hence larger variation in flow velocities) favours the formation of tidal couplets. A bed stratigraphy of SDLs and MDLs is not evident when the model is only forced by a M2 tidal constituent, though insignificant tidal couplets can still form during flood-ebb variations. Adding a boundary M4 constituent (thus creating a typically flood-dominated condition) tends to enhance the development of SDLs and favours the formation of tidal couplets. Besides, model results indicate that a larger boundary SSC generally favours the formation of tidal bedding, which is, however, partially dependent on the ratio of SSCs of different sediment (clay, silt, sand) types. Sediment properties, including grain size, settling velocity and critical shear stress for erosion, also play an important role on sediment sorting and tidal bedding dynamics. Potential impacts of some neglected processes such as wind waves, biological processes and alongshore tidal currents are also discussed and further research effort is needed to shed light on their influence.

# Acknowledgements

# Data availability

The model used for this study is an open-source software Delft3D developed and maintained by Deltares, the source code is accessible via https://oss.deltares.nl/web/delft3d. The field datasets used for model validation and comparison were all published and accessible. Any additional information needed to reproduce the work can be requested from the first author.

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1. Now at: Department of Geography, Museum Building Trinity College Dublin, Dublin 2, Ireland [↑](#footnote-ref-1)