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A conceptual framework for the erosion behaviour of sand–mud mixtures

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Abstract

The erosion behaviour of sand–mud mixtures is not well understood. As a first step, a conceptual framework for the erosion behaviour of sand–mud mixtures is proposed and validated with data from field and laboratory experiments based on appropriate parameters for cohesion and network structure. Six bed types with different characteristics are distinguished in relational diagrams. Validation with experimental data shows that observed transitions in erosion behaviour are clearly delimited in these diagrams. Mud content (% < 0.063 mm) as a descriptor for the transition between non-cohesive and cohesive erosion behaviour turns out to be less generic than the clay content (% < 0.004 mm). Furthermore, an estimation of the relevance of these compositional bed types in natural systems shows that the frequently observed constant ratio between clay and silt in the bed sediments of some depositional system strongly limits the number of relevant bed types in that system.

Keywords: Erosion; sand–mud mixtures; Sediment behaviour; Cohesion; Network structure

1. Introduction

Along rivers, estuaries and coasts, deposits of (non-cohesive) sand and (cohesive) mud are often observed. An understanding of the depositional processes and the ability to predict the dynamic behaviour of these sediments is necessary for sustainable management, maintenance and development of such systems. For example, large-scale erosion of sand along coasts can destabilise dunes and dikes, whereas the distribution of mud determines which areas collect pollutants, as these tend to adhere predominantly to cohesive sediments (cf. De Groot et al., 1982; Zwolsman et al., 1996).

Historically, many investigations have been carried out for (non-cohesive) sand beds and (cohesive) mud beds separately to improve our understanding of their erosion behaviour (Mitchener and Torfs, 1996). Based on these results, various conceptual models and mathematical formulations have been developed for the

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description and modelling of the erosion processes in sandy and muddy sediments. An extensive overview of these results is given by Van Rijn (1993) and Soulsby (1997) for (non-cohesive) sand beds and by Winterwerp (1989) and Whitehouse et al. (2000) for (cohesive) mud beds.

A major difference exists between the erosion formulations for sand and mud beds. Sand erosion is generally formulated in terms of a deviation with respect to a specific equilibrium situation. This equilibrium exists because sand deposition and erosion balance over alluvial beds in a uniform and stationary situation, and the equilibrium depends on the flow conditions and the sediment characteristics. Contrary to sand beds, the availability of mud is often limited and the flow is far from its transport capacity. Consequently, an equilibrium situation between mud deposition and mud erosion only exists in highly concentrated mud suspensions. Hence, the erosion formulations for mud beds do not include an equilibrium criterion, but only depend on the flow conditions and the bed properties.

Several recent erosion experiments have clearly demonstrated that the erosion characteristics can change dramatically when small amounts of mud are added to a sand bed (Bisschop, 1993; Mitchener and Torfs, 1996) or vice versa (Williamson and Ockenden, 1993). For example, Torfs (1995) measured a 2–5 times higher critical erosion shear stress than the critical shear stress for pure sand when 10% mud was added to the sand bed. In addition, the erosion rate strongly decreased with increasing mud content (cf. also Mitchener and Torfs, 1996). These results suggest that the erosion behaviour of sand–mud mixtures cannot be described by using the existing erosion formulations for pure sand (Van Rijn, 1993; Soulsby, 1997) or pure mud (Winterwerp, 1989; Whitehouse et al., 2000).

Based on laboratory and field experiments, several researchers identified a transition from non-cohesive to cohesive behaviour at increasing mud contents in a sand bed. Mitchener and Torfs (1996) suggested a transition range between 3% and 15% mud content ($\% < 0.063$ mm) for this transition. Other experimental data, however, suggest that the transition between non-cohesive and cohesive behaviour may occur at higher mud contents. For example, Houwing (2000) observed a clear transition in the erosion behaviour at a mud content of 20% during field experiments in the Wadden Sea (The Netherlands) (cf. also Houwing, 1999). These examples clearly demonstrate that the parameters governing the erosion behaviour of sand–mud mixtures, are not fully understood yet.

In this paper an attempt is made to integrate experimental results and knowledge of sediment beds in general in order to propose a conceptual framework in which the observed erosion behaviour of sand–mud mixtures is adequately represented (Section 2). In a second step, the conceptual model is verified by using experimental data from previous laboratory and field experiments (Section 3). Finally, the application potential of the proposed scheme to natural sedimentary systems is assessed (Section 4).

2. Conceptual framework

2.1. Limitations

The behaviour of sand beds under moderate flow conditions (say <1 m/s) is mainly characterised by the grain size distribution. In more dynamic flow regimes, the so-called 'sheetflow regime', permeability and package of a sand bed are also important (Bakker and Van Kesteren, 1998). A variety of bed properties influence the erosion behaviour of mud beds in natural systems (Berlamont et al., 1993). Important physical parameters for mud bed behaviour include grain size distribution, water content, type of clay minerals, permeability and compressibility; however several biological (e.g. organic content, bioturbation) and chemical parameters (e.g. chlorinity, pH) are also important (cf. Montague, 1986; Paterson, 1997; Black et al., 1998).

Although these parameters are presumably also of importance in sand–mud mixtures, it is currently not possible to parameterise many of them for use. Even for pure mud beds, the influence of several of the parameters is only partly and qualitatively understood (Winterwerp, 1989;

Whitehouse et al., 2000). Moreover, the role of chemical and biological parameters in previous erosion experiments with sand–mud mixtures was not investigated, which makes validation of these parameters impossible at present.

Hence, several assumptions have to be made. Firstly, only physical parameters are used to describe the erosion behaviour of sand–mud mixtures. Secondly, the sediment mixture is assumed to be homogeneous with depth and in the horizontal plane. Thirdly, it is assumed that physical parameters from tests on remoulded bed samples can be used in classifying and describing the erosion behaviour of mixed sediment beds. Remoulded bed samples are samples that have lost their original structural properties, which is generally the case in laboratory experiments. Finally, only erosion behaviour under moderate flow conditions is considered, say <1 m/s.

These assumptions limit the applicability of the proposed erosion framework. For example, old sediment layers exposed as a result of erosion can have a quite different erosion behaviour than remoulded samples with the same physical parameters as a result of their different stress and time history (e.g. overconsolidation and aging effects). Also horizontal heterogenity such as burrows formed by biological activity, will affect the erosion behaviour. Nevertheless, an erosion model based on the principal physical parameters should be able to illustrate changes in erosion behaviour when the sand–mud ratio is changing.

2.2. Parameters

Granular materials under 2 mm in diameter are commonly subdivided into sand (% 0.063–2 mm), silt (% 0.004–0.063 mm) and clay (% < 0.004 mm). The size fraction comprising silt and clay is known as mud or fines (% < 0.063 mm). However, it is important to note that only the clay particles within the mud fraction have cohesive properties. Therefore, a distinction between sand, silt and clay is adopted herein and the definitions and symbols are listed in Table 1.

It has long been known that natural sediment beds show different erosion behaviour as a function of their sand, silt, clay and water contents. Two important transition parameters are discussed hereafter: cohesion and network structure.

Table 1
Definitions and symbols for sediment fractions

Fraction	Grain size (mm)	Volume content (dimensionless)	Solid content (dimensionless)
Sand	0.063–2	ϕ_{sa}	P_{sa}
Silt	0.004–0.063	ϕ_{si}	P_{si}
Clay	<0.004	ϕ_{cl}	P_{cl}
Water		ϕ_w	

2.2.1. Cohesion

Historically, a distinction is made between non-cohesive and cohesive erosion behaviour (Raudkivi, 1990). Non-cohesive beds have a granular structure and the individual sediment particles do not stick together. The particle size, solid density, and particle shape are the dominant parameters influencing erosion in this case. Cohesive beds form a coherent mass because of electrochemical interactions between the sediment particles. These interactions strongly affect the erosion behaviour, whereas the particle size and density are of minor importance.

A sediment bed is called ‘cohesive’ when it exhibits a certain remoulded shear strength. Remoulded means that the in situ anisotropic and layered fabric is homogenised at constant water content resulting in an orientation invariant shear strength at large deformations. It appears that for most soils a relationship exists between the remoulded shear strength and the liquidity index (Van Kesteren et al., 1997). The liquidity index (LI) is expressed in terms of the actual water content (w) and the Atterberg limits (Mitchell, 1976):

$$LI = \frac{w - PL}{LL - PL}, \tag{1}$$

where LL is the liquid limit and PL the plastic limit. The liquid limit defines the transition from plastic to liquid behaviour and the plastic limit the transition from solid to plastic behaviour. Both indices relate to the water content of the sediment in question. The difference between the liquid limit and the plastic limit is defined as the plasticity index (PI) and can be estimated by (Mitchell, 1976):

$$PI = A(p_{cl} - n), \tag{2}$$

where p_{cl} is the clay content by dry weight, n the so-called 'offset' of the clay content (dry weight) and A the 'activity' of the clay mineral. The offset indicates the minimum clay content at which a sediment shows plastic behaviour. The offset for sand–mud mixtures is about 5–10% clay content (Mitchell, 1976). The activity is a measure for the binding capacities of the clay minerals and strongly depends on the type of clay. For example, the activity value for kaolinite is about 0.5, whereas the activity value for montmorillonite lies between 1 and 7 (Mitchell, 1976).

The liquidity index governs the transition between non-cohesive and cohesive behaviour in the following ways. First, the offset designates the critical clay content required to induce cohesive properties in a natural bed. Dyer (1986) and Raudkivi (1990) found that approximately 5–10% clay content by dry weight was sufficient for a natural bed to have cohesive properties. This corresponds to the measured range in offset (Mitchell, 1976). Secondly, the relationship between the remoulded shear strength and the liquidity index indicates that the remoulded shear strength increases with decreasing water content (i.e. increasing bed density) for a constant clay content by dry weight (cf. Eq. (1) and (2)). Thus, the cohesiveness of a natural sediment bed not only increases with increasing clay content by dry weight, but also with decreasing water content (cf. Postma, 1967).

2.2.2. Network structure

Although less well-known, the erosion behaviour also depends on the degree of packing or network structure in a sediment bed. When considering a sand bed without silt and clay, a network structure persists as long as the volume fraction of sand is large (dense packing), and sand particles are in close contact with each other (Fig. 1a). With increasing water content, the distance between the sand particles becomes larger and the contact between the particles decreases (loose packing). A critical network structure is reached at a so-called critical volume fraction for sand (ϕ_{cr}) (Fig. 1b). When the water content increases beyond this critical volume fraction, the sand particles loose contact with each other (Fig. 1c), and the sand–water mixture now behaves like a fluid (i.e. quick sand), although with a higher apparent viscosity because of the high sediment concentration.

The network structure of a sediment mixture is determined by the relative proportions of sand, silt and clay particles. In line with the above transition in network structure for pure sand, differences in erosion behaviour can be expected when the network structure changes from sand-dominated in silt-dominated or clay-dominated particle mixtures. From fluidization experiments it is known that sand particles form a network structure if the

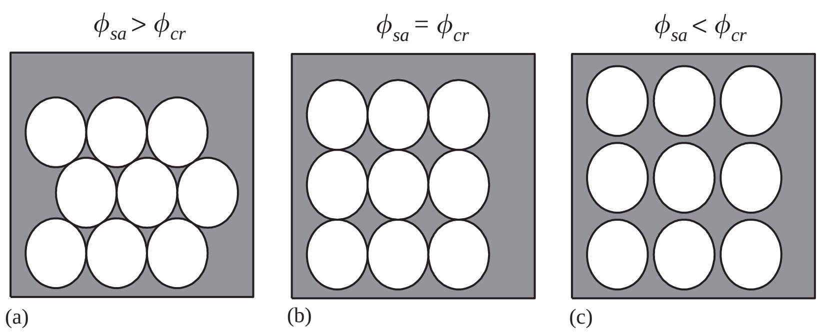

Fig. 1. Network structure in a sand bed for different volume fractions of sand.

volume fraction of sand (ϕ_{sa}) exceeds 40–50% (Merckelbach, 2000). Similarly, silt particles form a network structure if the volume fraction of the silt particles (ϕ_{si}) relative to the pore volume around the sand particles ($\phi_{si}/(1-\phi_{sa})$) is higher than 40–50%. In other cases, the clay fraction forms a network structure if sufficient clay is present in the sediment mixture. However, the clay content must be higher than the aforementioned offset in order to form a network structure.

2.3. Relational diagram

In the previous section it was argued that transitions in erosion behaviour can be expected when (i) the bed changes from non-cohesive to cohesive, and (ii) the network structure is formed by another sediment fraction. Appropriate parameters were defined for both transitions, being mainly dependent on the relative proportions of the sand, silt and clay fractions by dry weight and by volume.

The transitions for cohesion and network structure can be visualized in a sand–silt–clay triangle (Fig. 2) in which the sand, silt and clay contents by dry weight vary along the axes. The horizontal line indicates the transition between non-cohesive (below) and cohesive (above) mixtures. The transition ranges between 5% and 10% clay content. The average content of 7.5% is chosen in Fig. 2 to delimit non-cohesive and cohesive mixtures. The dashed lines in the left-hand corner of Fig. 2 indicate the boundary of a sand-dominated network structure for different volume fractions of water (ϕ_w). This transition is determined by the volume fraction of sand

$$\phi_{sa} = (1-\phi_w)p_{sa}. \tag{3}$$

Consequently, the position of this transition in a sand–silt–clay triangle not only depends on the volume fraction of sand, but also on the volume fraction of water. The minimum volume fraction of sand required to form a sand-dominated network structure is 40%. If the solid particle density equals $\rho_s = 2650\,\mathrm{kg/m^3}$ then the volume fractions of water $\phi_w = 40\%$, 45% and 50% correspond to dry bed densities of 1590, 1458

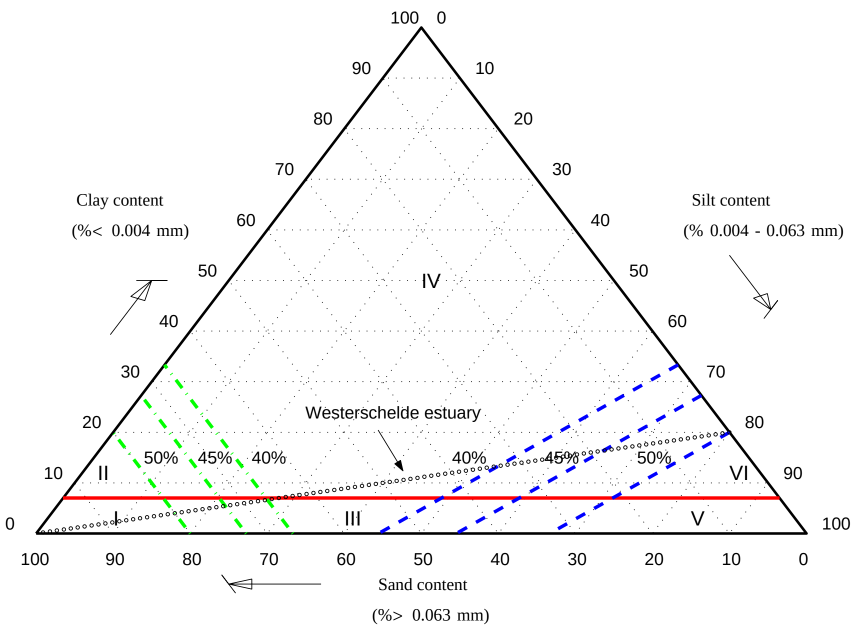

Fig. 2. Sand–silt–clay triangle with transitions for cohesion and network structure. I = non-cohesive sand-dominated, II = cohesive sand-dominated, III = non-cohesive mixed, IV = cohesive clay-dominated, V = non-cohesive silt-dominated, and VI = cohesive silt-dominated network structure.

and 1325 kg/m^3, respectively. The dashed lines in the right-hand corner of Fig. 2 indicate the transition of a silt-dominated network structure for different volume fractions of water. This transition is determined by the volume fraction of silt relative to the pore volume around the sand particles:

$$\frac{\phi_{si}}{1-\phi_{sa}} = \frac{(1-\phi_w)p_{si}}{1-(1-\phi_w)p_{sa}}. \qquad (4)$$

Hence, the position of this transition in the sediment triangle also depends on the volume fraction of water. The settings of these transitions are analogous to the sand-dominated transitions with $\phi_{si}/(1-\phi_{sa}) = 40\%$ and $\phi_w = 40\%$, 45% and 50%, respectively.

Based on the sand–silt–clay triangle, six textural bed types indicated by Roman numbers in Fig. 2 can be distinguished (cf. also Table 2). Sediment beds in the lower left-hand corner and lower right-hand corner of the sediment triangle have a sand-dominated (I and II) or silt-dominated (V and VI) network structure, respectively. In the remainder of the diagram, the network structure is dominated by clay if sufficient clay is present (IV). In area III none of the individual size fractions are large enough to form the network structure by themselves and all three sediment fractions therefore contribute to the network structure. The horizontal line at an average clay content of 7.5% separates sediment mixtures which are cohesive (II, IV and VI) or non-cohesive (I, III and V).

Table 2
Overview of various bed types

Number	Cohesion	Network structure
I	No	Sand
II	Yes	Sand
III	No	Mixed
IV	Yes	Clay
V	No	Silt
VI	Yes	Silt

Other diagrams have been proposed to classify sediments composed of sand–silt–clay mixtures in natural systems without, however, considering aspects such as cohesion or network structure. Two well-known diagrams are those proposed by Shepard (1954) and Folk (1954) (see also Flemming, 2000) which are shown in Fig. 3. It is immediately evident that the subdivisions proposed in Fig. 2 do not coincide with either Shepard's or Folk's diagram. The main reason is that the transitions used in the Shepard's and Folk's diagram (e.g. 25%, 50% and 75%) are rather crude and arbitrary, whereas the transitions in Fig. 2 have a physical background. Nevertheless, a superimposition of the scheme presented in this paper on the scheme of Folk (1954) or later derivatives of it (e.g. Pejrup, 1988; Flemming, 2000) would have the benefit of combining a textural classification with structural attributes of a sediment.

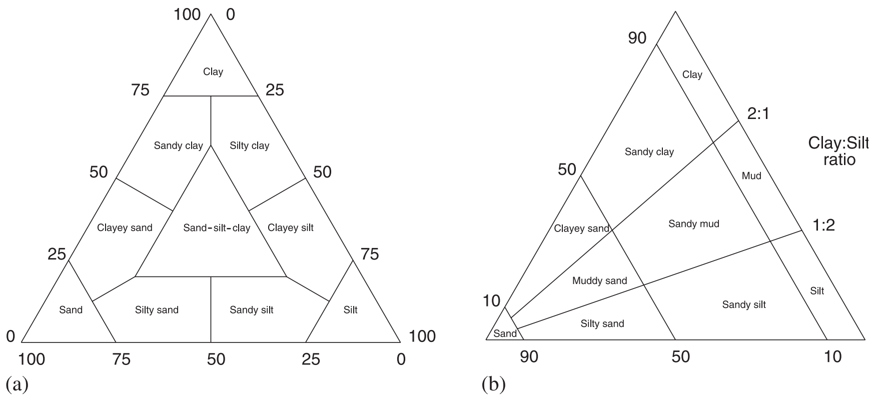

Fig. 3. Classification diagrams for sand–silt–clay mixtures after Shepard (A) and after Folk (B).

3. Experimental validation

The proposed subdivision is validated using experimental results from previous laboratory and field experiments. Several authors investigated the transition to cohesion, but the effect of the network structure was not investigated. Therefore, experimental data from Torfs (1995) were re-analyzed to establish this transition.

3.1. Cohesion

Murray (1977) performed laboratory experiments with three mixtures of uniform coarse sand and mud. The mud percentages for these mixtures were 0%, 10% and 18% and the clay percentage were 0%, 1.0% and 1.8%. No information was given about the water content or dry bed density. During these experiments the sediment transport rate of the coarse sand fraction was measured as a function of the applied bed shear stress. Because the clay content was much less than 5–10%, non-cohesive behaviour would be expected for all the experiments. Indeed, Murray's observation that the coarse sand was transported as bed load and mud was easily suspended is in agreement with the subdivision proposed in this paper.

Alvarez-Hernandez (1990) carried out erosion experiments with mixtures of clay (Laponite) and various sand grain sizes. It was concluded that the transition between cohesionless and cohesive behaviour occurred in the range from 5% to 15% clay content by dry weight depending on the sand grain size. Again, these experimental results agree well with the clay content range 5–10% beyond which a sediment mixture exhibits cohesive properties suggested in this paper.

Torfs (1995) investigated the erodibility of artificial sand–mud and natural sand–mud mixtures (cf. also Mitchener and Torfs, 1996). Only the artificial sand–mud mixtures with high bed density are considered herein, because only a few natural mixtures and artificial mixtures with low bed density were examined. The characteristics of these experiments are summarized in Table 3. Two muds of different composition were added to fine sand and the erodibility was tested for a certain mud content range by dry weight. The wet bed density was kept constant for all mixtures. Transitions from non-cohesive to cohesive behaviour were observed at a certain 'critical mud content'. For a low mud content, ripples were observed, indicating bed load transport of sand, fine particles being washed out from the top layer. Above the critical mud content the mixtures showed typical cohesive (mass or surface) erosion. For kaolinite mixtures, an abrupt change from non-cohesive into cohesive behaviour was observed at a critical mud content of 4%. The montmorillonite mixtures showed typical cohesive behaviour above 13% mud content. Moreover, the montmorillonite mixtures showed a transition zone between 7% and 13%, in which the behaviour could be defined neither non-cohesive nor cohesive.

The transition values between non-cohesive and cohesive behaviour observed by Torfs (1995) can be translated in terms of clay content by using the sand–silt–clay distribution in Table 3. Thus, the transition value for the kaolinite mixtures lies at 3.4% clay content, and that for the montmorillonite mixtures at 3–5% clay content. In both cases, the clay content at the transition is about the same, although the mud contents differ strongly. This clearly agrees with the subdivision proposed in this paper, and also indicates that it is the clay content, and not the mud content, which determines the transition between non-cohesive and cohesive

Table 3
Characteristics of sand-mud mixtures used by Torfs (after Torfs, 1995)

Sand grain size (mm)	Mud type	P_{sa} (dimensionless)	P_{si} (dimensionless)	P_{cl} (dimensionless)	Mud content (%)	Wet bed density (kg/m^3)
0.23	Kaolinite	0	0.15	0.85	0–15	1850
0.23	Montmorillonite	0.09	0.49	0.42	0–28	1850

behaviour. The slightly low value of the clay content as compared with the suggested range 5–10% can be explained by the relatively high bed density.

Panagiotopoulos et al. (1997) performed erosion experiments with two different sand grain sizes. Sand–mud mixtures were prepared with natural mud, ranging from 0% to 50% mud content. The data show an increasing erosion threshold for both grain sizes as the mud content increases from 0% to 50%. Moreover, the increase in erosion threshold is relatively small for mud contents smaller than 30% (i.e. clay contents less than 10%), but much higher for mud contents between 30% and 50%. Finally, the erosion threshold was about the same for both sand grain sizes when the mud contents reached 50%. Panagiotopoulos et al. (1997) already actually pointed out that the transition in behaviour agreed well with the concept of a "critical clay content" at 5–10% proposed in earlier publications (Dyer, 1986; Raudkivi, 1990).

Houwing (2000) measured the erosion rate of natural sand–mud beds in the Wadden Sea (The Netherlands). He observed a transition in erosion behaviour at mud contents of 20–30% by dry weight. According to Van Ledden (2003), the mud content in this area exceeds the clay content by a factor 4–5. Thus, the observed transition in mud content corresponds to a clay content of 5–7%, which agrees again with the subdivision proposed here.

3.2. Network structure

Torfs (1995) did not study the effect of a change in network structure with increasing mud content. A re-analysis of these data was therefore carried out to estimate the transitions in network structure during the experiments. The wet bed density was 1850 kg/m^3 which corresponds to a water content of $\phi_w = 0.485$. If a minimum volume fraction of sand is assumed ($\phi_{sa} = 0.45$), then a sand-dominated network structure would have been present in samples with less than 13% mud content by dry weight (cf. Eq. (3)). Above 13% mud content, the network structure would no longer have been sand-dominated. As pointed out before, the transition between non-cohesive and cohesive behaviour occurred at a clay content of 3–5% in these experiments.

The transitions in cohesion and network structure as a function of mud content and the content of kaolinite and montmorillonite, respectively, are presented in Fig. 4. The Roman numbers correspond to the bed types in Table 2.

It can be seen that, with the exception of a single point at the upper limit (15%), the network structure in the kaolinite mixture was sand-dominated (Fig. 4). Furthermore, the network structure was also sand-dominated at the transition between non-cohesive to cohesive behaviour. This indicates that the change from non-cohesive to cohesive behaviour at increasing kaolinite contents is rather abrupt, a feature which is consistent with the observations. However, the network structure for the montmorillonite mixtures changes from sand-dominated at low mud contents to clay-dominated at high mud contents. At the same time, the sediment bed also changes from non-cohesive into cohesive behaviour. This suggests a more gradual change from non-cohesive to cohesive bed behaviour. This clay-mineral specific response probably explains the transition zone in bed behaviour between 7% and 13% mud content observed by Torfs (1995). The bed behaviour in this zone would be difficult to interpret as either non-cohesive or cohesive.

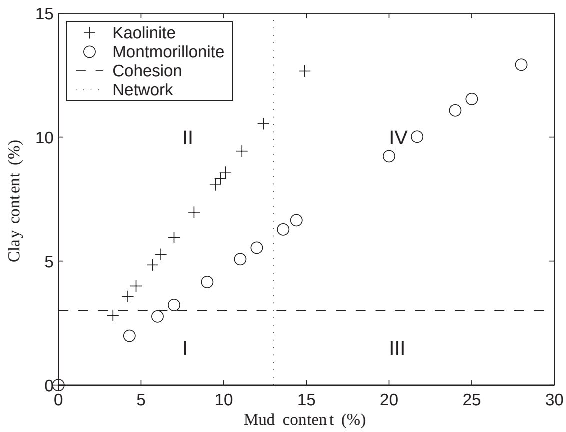

Fig. 4. Transition in cohesion and network structure for kaolinite and montmorillonite mixtures (after Torfs, 1995). The Roman numbers refer to the bed types in Table 2.

4. Application to natural systems

It is not expected that all bed types distinguished in the previous sections actually play an important role in the real world. Often, the ratios between the clay and silt content in natural deposits are fairly constant (e.g. Pejrup, 1988; Flemming, 2000; Van Ledden, 2003). As an example, the clay/silt ratio ($p_{cl}/p_{si} = 0.24, R^2 = 0.85$) for the Westerschelde (The Netherlands) is illustrated in Fig. 2. A constant ratio between clay and silt would correspond to a straight line in the sand–silt–clay triangle, which limits the number of possible bed types in this system.

The importance of the proposed bed types can be estimated by using empirical relationships for the dry bed density and the remoulded shear strength. Based on field measurements, Allersma (1988) proposed an empirical relationship between the sand content and the dry bed density (ρ_{dry}):

$$\rho_{dry} = 480\alpha_c + (1300 - 280\alpha_c)p_{sa}^{0.8}, \tag{5}$$

where α_c is a consolidation coefficient, ranging from 0 (fresh deposits) to 2.4 (old deposits).

The relationship between the liquidity index and the remoulded shear strength is estimated by using the data of Van Kesteren et al. (1997)

$$f_u = 10^{0.4LI^2 - 2.3LI + 2.2}. \tag{6}$$

In the present study, a minimum value of $0.1\,\mathrm{kN/m^2}$ has been applied herein for the remoulded shear strength to distinguish non-cohesive and cohesive behaviour. A constant value of 25% has been applied for the plastic limit in Eq. (1). The offset n for the clay content by dry weight has been set at 7%, and the activity A equals 3 in Eq. (2). Such values are fairly representative for marine deposits in the Netherlands.

Based on these relationships, the bed types in this environment can be visualized as a function of the sand content and the dry bed density (Fig. 5). The dashed lines indicate the transition between non-cohesive (above) and cohesive (below) behaviour for clay/silt ratios equal to 0.33, 1.0 and 3.0. The different network structures are shown by different shadings: silt-dominated (black area), clay-dominated or mixed (white area) and sand-dominated (grey area). The numbers indicate the different bed types as defined in Fig. 2 and Table 2. Finally, the black lines are plotted according to Eq. (5) for fresh ($\alpha_c = 0.0$) and consolidated ($\alpha_c = 2.4$) deposits. Natural combinations of sand content and dry bed density are found between these lines.

In Fig. 5, silt-dominated bed types fall outside the area in which natural combinations of sand–silt–clay mixtures commonly occur. Bed type VI is

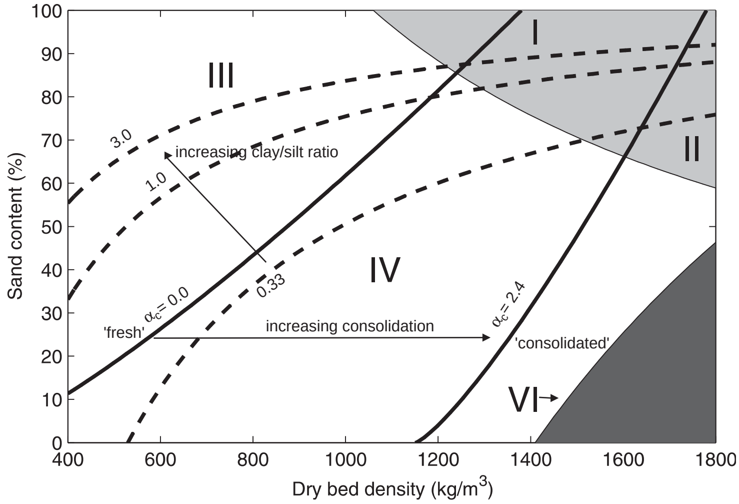

Fig. 5. Estimation of relevant bed types in natural systems.

present, but bed type V falls outside the given range of dry bed density in Fig. 5. Thus, only for very low clay/silt ratios, silt-dominated bed types will be important. In addition, a relatively large area is covered by bed type I (non-cohesive sand-dominated) and IV (cohesive clay-dominated) for all clay/silt ratios. Finally, the importance of bed types II and III strongly depends on the clay/silt ratio. For high clay/silt ratio (>3), only bed type II is important, whereas for low clay/silt ratio (<0.33) bed type II can be neglected. For bed type III, the opposite applies.

5. Conclusions

A conceptual framework for the erosion behaviour of sand–mud mixtures has been developed using appropriate parameters for cohesion and network structure. On this basis, six bed types have been distinguished. The following conclusions can be drawn:

- The agreement between the subdivisions of the framework and experimental data from laboratory investigations demonstrate that the approach has a sound physical basis. Especially the transition between non-cohesive and cohesive behaviour at a clay contents of 5–10% for natural sediment beds is validated by the experimental data. This also indicates that the 3–15% mud content range for this transition, as suggested by Mitchener and Torfs (1996) and Whitehouse et al. (2000), is inappropriate.
- A re-analysis of the experimental data of Torfs (1995) shows that the observed differences in erosion behaviour of kaolinite and montmorillonite mixtures can be explained by the transitions in network structure. This aspect has not been given enough attention in previous studies. It is recommended to study this aspect more systematically in future work.
- An assessment of prevailing bed types in natural systems shows that constant clay/silt ratios determine which bed types occur are important. The analysis also indicates that natural silt-dominated bed types rarely occur in natural systems are rare in systems for which Eq. (5) holds.
- Since the cohesion and the network structure transitions can be represented in sand–silt–clay diagrams, the resulting classes can be combined with the existing textural classifications based on ternary diagrams.

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