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Original Research

Impact of the solid volume fraction of clay and consolidation on the erodibility of sand-mud mixtures

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ABSTRACT

The erodibility of sediment mixtures is a key factor in sediment dynamic processes and morphological evolution in coastal environments. However, it remains insufficiently understood. In the current study, the critical shear stress of sediments is analyzed with different mud contents and consolidation degrees from experimental results and previous studies. The results indicate that the critical shear stress increases with clay content, peaking at 30% clay content, and then gradually decreasing. Compared to the solid volume fraction of mud (clay and silt), the solid volume fraction of clay shows a higher relation with the critical shear stress of sand-mud mixtures. The role of the consolidation degree in the erodibility of sediment mixtures was quantified through consolidation experiments, revealing an exponential relation between critical shear stress and consolidation coefficient. An empirical equation for the critical shear stress is proposed to consider the mud content, the solid volume fraction of clay, and the consolidation degree. This equation is applicable to mixed sediment over the full range of mud content and varying consolidation degrees. It has a simple form, is easier to apply, and outperforms other empirical equations (RMSE = 0.62; $R^2 = 0.73$).

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1. Introduction

In natural environments, sediment largely exists as mixtures of sand and mud. Mud is a mixture of clay, silt, a small amount of sand, organic matter, and water (Winterwerp & van Kesteren, 2004). The erodibility of sediment mixtures, especially cohesive sediment, is more complex than that of non-cohesive sediment because of the complex interplay among various factors, including physical, biological, and geochemical factors (Grabowski et al., 2011). The critical shear stress is a fundamental parameter that affects sediment transport, and, subsequently, plays a role in morphological evolution. Several studies have focused on the effect of sediment properties on the erodibility of sediment mixtures (Kothyari & Jain, 2008; Mitchener & Torfs, 1996; Murray, 1977; van

Ledden et al., 2004; van Rijn, 2020a); however, the predictability of the erodibility of sediment mixtures is still uncertain.

Physical properties, including sediment components, water content, and bulk density, are closely related to the erodibility of sand-mud mixtures (Kothyari & Jain, 2008; Ockenden & Delo, 1988; Panagiotopoulos et al., 1997; van Ledden et al., 2004; Wu et al., 2018). Generally, the critical shear stress increases with increasing clay/mud content (Grissinger et al., 1981; Mitchener & Torfs, 1996; Nalluri & Alvarez, 1992; Torfs et al., 2000). Experimental results indicate that sediment exhibits cohesive behavior when the mud content ranges from 3% to 15% (Mitchener & Torfs, 1996) or is around 20% (Houwing, 1999), and when the clay content ranges from 5% to 10% (van Ledden et al., 2004). Thus, the threshold is ambiguous and varies depending on sediment properties. The mud volume fraction indicates both consolidation and mud content, and is highly related to sediment erodibility (Dickhudt et al., 2011; Grabowski et al., 2011; Le Hir et al., 2008). Similar to mud volume fraction, studies have argued that the dry bulk density of mud, which is equal to the mud volume fraction multiplied by the sediment bulk density, is a key factor in the

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erodibility of sediment mixtures (Chen et al., 2018; Perera et al., 2020; Wu et al., 2018).

Recent studies have also demonstrated the importance of clay in the erosion behavior of sand-mud mixtures (Ahmad et al., 2018; Torfs, 1995; van Rijn, 2020b; Zheng & An, 2017). The cohesive force between sediment particles is mainly controlled by clay content and water content (Postma, 1967; van Ledden et al., 2004). Cohesive sediment has bonds whose strength is closely linked to pore water chemistry and clay mineralogy, which, in turn, govern bed erosion resistance (Arulanandan, 1975; Kelly & Gularte, 1981). As for particle size, only a mud particle size of less than 8 μm , which includes very fine silt and clay, displays strong cohesion (van Rijn, 2020a; Yao et al., 2022). Moreover, the clay content is considered a more suitable indicator for explaining the transition from non-cohesive to cohesive sediments (van Ledden et al., 2004). While some studies have suggested that critical shear stress is more related to mud content than clay content (Le Hir et al., 2008). It remains inconclusive which of these two factors (clay or mud content) plays a key role in determining the erodibility of sand-mud mixtures.

In addition to the mud content, the degree of consolidation is essential to the erodibility of sediment mixtures. The consolidation of sediment mixtures mainly includes self-consolidation (Sharif, 2003; Smith et al., 2015) and pressurization (Gao et al., 2019; Ye et al., 2011, pp. 973–983). Critical shear stress can vary by several orders of magnitude depending on the consolidation state (Le Hir et al., 2008). Bulk density is a key parameter of the degree of consolidation and is closely related to cohesive sediment erodibility (Houwing, 1999; Krone, 1999; Li et al., 2023; Sharif, 2003; Wang, 2013; Ye et al., 2011, pp. 973–983). Previous settling and consolidation tests have shown that the consolidation degree is affected by different sediment compositions (Fossati & Piedra-Cueva, 2015; Marion et al., 1992; Ockenden & Delo, 1988; Williamson & Ockenden, 1992). Under the same conditions, with increased sand content, the degree of consolidation increased, and when sand content exceeded 30%, the sediment consolidated rapidly (Torfs et al., 1996; van Rijn & Barth, 2019).

Several laboratory studies have been done on cohesive sediment with varying consolidation, focusing on both erosion threshold (Kamphuis & Hall, 1983; Laflen & Beasley, 1960; Shu et al., 2020; Zreik et al., 1998) as well as erosion rate (Nafchi et al., 2021; Ockenden & Delo, 1988; Tan et al., 2010). Critical shear stress increases with consolidation duration or pressure (Kamphuis & Hall, 1983; Parchure & Mehta, 1985; Shu et al., 2020; Zreik et al., 1998), while the erosion rate decreases with consolidation duration under the same shear stress (Nafchi et al., 2021). Compared to the numerous studies on mud erosion under different consolidation conditions, only a few studies have investigated the erosion of sediment mixtures at varying consolidation depths (Sharif, 2003; Wang, 2013). The effect of the degree of consolidation on the cohesion of sediment mixtures, and, thus, the erodibility of sand and mud mixtures, remains poorly explored.

Accurate estimation of the critical shear stress is crucial for practical applications. Despite the numerous empirical formulas proposed for estimating the critical shear stress for cohesive and non-cohesive sediment, their applicability to sand-mud mixtures remains limited due to the complex influencing factors and the wide range of sediment sizes. Studies on predicting the critical shear stress of sand-mud mixtures primarily include empirical (van Rijn, 1993; Wang, 2013; Ye et al., 2011, pp. 973–983) and theoretical equations (Chen et al., 2018; Wu et al., 2018; Yao et al., 2022). Many studies have linked critical shear stress to sediment properties, such as bulk density (Ahmad et al., 2018; Mitchener & Torfs, 1996), clay content (Wang, 2013; Zheng & An, 2017), water content (Wang, 2013), void ratio (Kothiyari & Jain, 2008), and mud

content (Ahmad et al., 2011; Ye et al., 2011, pp. 973–983). Empirical equations typically utilize the critical shear stress of pure mud and sand in a piecewise function (van Ledden, 2003; van Rijn, 2020b).

Theoretical equations can also be used based on the force balance equation, but applying them can be quite complicated. Accounting for the sediment filling theory (Wu & Li, 2017), the solid/void volume ratio was included in the equation and can be used for sand-mud mixtures as well as pure sand or pure mud sediment (Wu et al., 2018). The ratio of the dry bulk density of the mud to the stable dry bulk density was regarded as an index of the cohesive force in the study of Chen et al. (2018). The stable dry bulk density is difficult to calculate from available literature data, as it requires the particle size distribution. Thus, a new piecewise equation was developed which includes particle size, mud content, dry bulk density, and the critical mud content, i.e., $P_{\text{mcr}} = 15\%$ (Chen et al., 2021). The formula, proposed in various forms, incorporates several coefficients determined from specific experimental data, making it inconvenient for practical applications. To improve the prediction of the erosion threshold, the main factors affecting the erodibility of sediment mixtures must be determined.

The objectives of the current study are as follows: first, to understand the effect of sediment properties on the erodibility of sediment mixtures and to assess specific effects of clay and mud content; second, to quantify the role of the degree of consolidation on the erodibility of sediment mixtures as mud content increases, and, third, to develop a simpler and more accurate empirical equation for the critical shear stress of sand and mud mixtures.

2. Materials and methods

2.1. Materials

Two types of mud were considered in the current study—one collected from the field and the other from artificial samples, designated as Chongming and Kaolin, with median particle sizes of 10.5 and 3.9 μm , respectively. The sand was collected from the field, with a median particle size of 120 μm (Fig. 1). The uniformity of sediment is defined by the gradation index (GI), given by the formula: $GI = 0.5 (d_{84} / d_{50} + d_{50} / d_{16})$, where d_x is the diameter of below which x percent of the particles are finer. The diffraction spectrum revealed that Chongming samples primarily contained quartz (58.8%), kaolinite (13.8%), illite (11.6%), chlorite (9.2%), and montmorillonite (6.6%), while kaolin samples were mainly composed of quartz (27%) and kaolinite (73%).

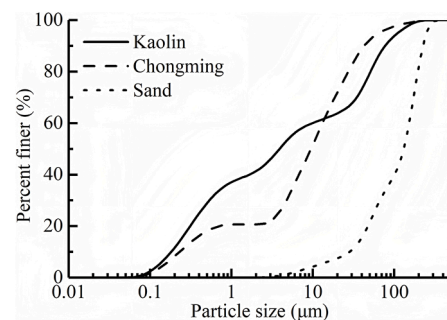


Fig. 1. Particle size distribution of the samples.

Samples were prepared with mud content ranging from 0 to 70% of the dry weight of mud. The samples were labeled with IDs according to the mud content (kaolin, abbreviated as K; Chongming, abbreviated as CM). As for the sediment size, mud is defined as the particle size below 63 μm , with the particle mixtures of clay (< 4 μm) and silt (4–63 μm). The experimental samples were divided into the following two groups: one consisting of sand mixed with kaolin (e.g., 10%K) and the other comprising a mixture of sand and field mud (e.g., 10%CM). Subsamples were prepared for all samples to measure sediment particle size, dry bulk density, water content, and porosity. These subsamples also were analyzed to determine the consolidation degree and compared with other experimental results. The physical properties of the samples are listed in Table 1. To maintain consistency with other studies (e.g., Wang, 2013; Ye et al., 2011, pp. 973–983), the sediment content is defined as the dry weight of sediment. As mud content increases, bed structures change, resulting in decreased dry bulk density and increased porosity, indicating a transition from dense to soft bed states (Table 1).

2.2. Sample preparation

Field samples were oven-dried at 60 °C for 48 h to a constant weight. After drying, the field samples were sifted through 10 mesh screens to remove shells and vegetation roots. Subsequently, all samples were weighed and mixed with tap water based on the specified wet bulk density ($\rho_b = 1,400 \text{ kg/m}^3$). All the mixed sediments were mechanically stirred for 15 min to ensure the uniformity of the samples. The sediment was placed in the annular flume layer by layer, followed by gently pressing with a hand roller to reduce air in the bed structure. Afterward, the surface was leveled to a thickness of 5 cm with a scraper to minimize surface unevenness that could influence the onset of sediment erosion (Fig. 2(b)).

After the sediment was prepared, tap water was slowly poured on the bed to reduce surface disturbance. All sediment samples then underwent 12 h of consolidation under 18 cm deep water to achieve a uniform water content. All the samples were assumed to be in a saturated state, with the pores filled with water, and the presence of air was ignored.

For the 30%, 50%, and 70%CM samples, additional subsamples were prepared with different consolidation degrees to study the effect of consolidation on critical shear stress. The three groups of samples were prepared with different water contents, reflecting sediments in different consolidation states. As water content increased, the samples transitioned from a compact to a soft state. Although the 50%CM samples were prepared after the other two samples, all samples were prepared under identical conditions, including the same consolidation and mixing methods. Also, their critical shear stress was measured using a rheometer at a constant temperature of 20 °C.

2.3. Experimental setup

An annular flume that can reproduce natural hydrodynamic conditions, particularly calm, wave-free conditions, was utilized to measure sediment erodibility (Fig. 2(a)) (Pope et al., 2006). Previous studies using the same apparatus have demonstrated the applicability and credibility of this flume erosion testing procedure (Bartzke et al., 2013; Pope et al., 2006; Widdows et al., 1998). The flume consisted of two concentric cylinders with diameters of 65 and 45 cm, forming a 10-cm width flow channel in between (Fig. 2(a)). A motor-driven rotor ring lid with a central diameter of 55 cm was placed on top of the flume and submerged in 2 cm of water. The motor rotated the paddle with the lid, driving the water flow (Fig. 2(a)). The lid rotation speed increased from 5 to 60 r/min, producing a current velocity of 5–55 cm/s in the flume. The system ran with a step of 5 cm/s, each flow speed lasted 15 min to obtain stable turbidity. Each experiment continued for 180 min until mass erosion occurred at the bed surface.

A sideways-looking acoustic Doppler velocimeter (Nortek Vectrino ADV) was utilized to measure three dimensional (3D) flow velocity (Fig. 2(b)). The instrument probe was positioned in the middle of the channel, 7.5 cm above the bed, to measure the near-bed velocity at 2.5 cm above the bed. The flow velocity was measured at a frequency of 100 Hz.

A turbidity meter (optical backscatter sensor, OBS300) was positioned at a height of 2.5 cm above the bed to record the near-bed suspended sediment concentration and was logged on the computer at 1 Hz (Fig. 2(b)). Water samples were extracted through a sampling port (5 mm in diameter) 2.5 cm above the sediment surface to calibrate the OBS sensor.

Sediment grain size fractions were determined using a Coulter LS-100Q (range: 0.05–2,000 μm) after digestion in 10% hydrogen peroxide and 10% hydrochloric acid. Water content and sediment porosity were derived by drying the sample in an oven at 80 °C for 48 h.

There are many criteria for determining the sediment erosion threshold, such as the erosion rate (Jacobs et al., 2011), the threshold of suspended sediment concentration (SSC) (Yao et al., 2022), and the sharp increase in SSC (Ha et al., 2018). The results of the three methods were compared, revealing a strong correlation coefficient of determination ($R^2 = 0.94$) and an average relative error of 6.82%. The sharp increase in SSC was chosen as the criterion for the erosion threshold in the current study. As seen in Fig. 3, the SSC exhibited a sharp increase at a motor speed of 55 r/min. Therefore, the erosion threshold of the 30%K sample was determined by the current velocity at that motor speed.

Due to limited remaining material and the difficulty of ensuring sample consistency through resampling, flume measurements were not done for the three groups of samples (30%, 50%, and 70% CM) with different degrees of consolidation. The yield stress, measured using a rheometer, was utilized to estimate the critical

Table 1
Sediment properties for all sample treatments.

Sample ID	Mud content (%dry weight)	Wet bulk density (kg/m^3)	Dry bulk density (kg/m^3)	Water content (%)	Composition (%)			d_{50} (μm)	GI	Porosity (%)
					Clay	Silt	Sand			
0%K	0	2.14	1.65	29.9	0.8	27.6	71.6	132.2	2.4	37.7
10%K	10	2.10	1.52	38.2	13.9	29.7	56.4	88.6	9.3	42.5
30%K	30	1.89	1.20	56.0	26.2	26.1	47.7	60.9	15.6	54.6
50%K	50	1.52	0.96	57.9	46.0	33.0	21.0	3.8	10.1	63.6
70%K	70	1.44	0.75	93.0	56.8	30.0	13.2	3.3	6.5	71.8
10%CM	10	1.69	1.27	33.2	3.5	41.0	55.5	81.1	4.6	52.0
30%CM	30	1.70	1.23	37.9	8.1	43.8	48.1	52.5	5.6	53.4
50%CM	50	1.64	1.07	52.9	12.9	54.2	32.9	25.3	5.8	59.5
70%CM	70	1.53	0.93	64.8	15.4	61.3	23.3	17.3	5.5	65.0

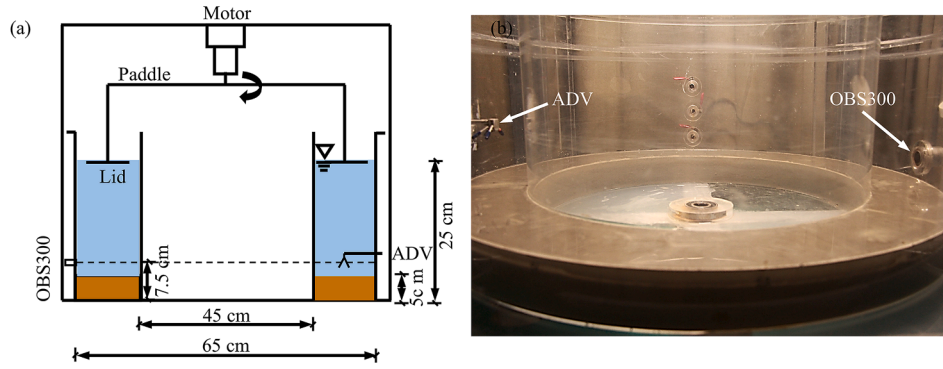


Fig. 2. Schematic (a) and photograph (b) of the annular flume.

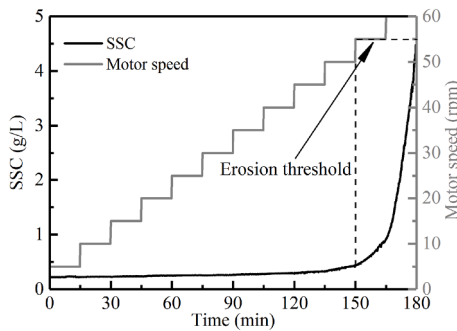


Fig. 3. Erosion process for 30%K samples.

shear stress of samples with different degree of consolidation. The yield stress was determined using an Anton Paar MCR 302 rheometer with a parallel plate (50 mm in diameter) system. The plate rotated with an increased shear stress of 0.01–500 Pa. Then, the yield stress was converted to the critical shear stress through an empirical equation (Eq. (8)) described in Section 2.4.

2.4. Data processing

The velocity data were first filtered to remove poor-quality data (beam correlations < 70% and signal-to-noise ratios < 12) (Yao et al., 2022). Subsequently, the turbulent kinetic energy (TKE) was used to calculate the bed shear stress (Kim et al., 2000; Pope et al., 2006) as Eq. (1):

$$TKE = 1 / 2\rho(u'^2 + v'^2 + w'^2) \tag{1}$$

where ρ is the density of the fluid, u' is the fluctuating flow velocity in the streamwise direction, and v' and w' denote cross-channel and vertical components of the flow velocity, respectively. The ratio of TKE to bed shear stress, τ_0 , is constant (Pope et al., 2006) and is represented as Eq. (2):

$$\tau_0 = C1 \cdot TKE \tag{2}$$

where $C1 = 0.19$.

The OBS sensor was calibrated using water samples collected at each velocity step. The extracted water samples were filtered,

dried, and weighed during the erosion experiments. The SSC was calibrated for each sample to reduce the influence of the particle size on the turbidity.

The consolidation coefficient, proposed by Allersma (1988), was applied to quantify the degree of consolidation. The relation among the consolidation coefficient, sand content, and dry bulk density for sediment mixtures was established as Eq. (3):

$$\rho_d = 480\alpha_c + (1,300 - 280\alpha_c)P_s^{0.8} \tag{3}$$

where ρ_d is the dry bulk density, α_c is the consolidation coefficient, and P_s is the sand content.

The solid volume fraction of mud was defined as the ratio of the mud volume to the total volume of mud and water. It was calculated as a function of the volume fraction of total solids, which is the ratio of the solids volume to the total volume, which is computed as Eqs. (4) and (5) (Dickhudt et al., 2011):

$$\phi_{sm} = \frac{\phi_{stot} - P_s \cdot \phi_{stot}}{1 - P_s \cdot \phi_{stot}} \tag{4}$$

$$\phi_{stot} = \frac{\rho_b - \rho_w}{\rho_s - \rho_w} \tag{5}$$

where ϕ_{sm} and ϕ_{stot} are the solid volume fraction of mud and the total solid volume fraction, respectively; and ρ_b is the sediment bulk density, ρ_w is the water density, and ρ_s is the density of sediment particles.

Similar to the definition of the solid volume fraction of mud, the solid volume fraction of clay was calculated as the ratio of the volume of clay to the total volume of clay and water, as Eq. (6):

$$\phi_{clay} = \frac{P_{clay}}{\omega + \frac{P_{clay}}{\rho_s}} \tag{6}$$

where ϕ_{clay} is the solid volume fraction of clay; P_{clay} and P_s are the clay and sand contents, respectively; and ω is the water content.

The root-mean-square error (RMSE) was used to evaluate the accuracy of the empirical equation. The RMSE between the measured and predicted values is defined as Eq. (7):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_m - y_p)^2}{n}} \tag{7}$$

where n , y_m , and y_p are the sample size, measured value, and predicted value, respectively.

The critical shear stress of the samples with varying consolidation degrees was estimated based on an empirical equation that considers the yield stress. Several empirical equations have been proposed to describe the relation between the critical shear stress and yield stress (Dzuy & Boger, 1983; Otsubo & Muraoka, 1988; Pang, 2011; Zhang & Yu, 2017). Similar to the sediment collection and preparation methods described by Pang (2011), the current samples also were collected from coastal areas and prepared with varying bulk densities. The equation proposed by Pang (2011), is widely utilized in estuary environments and proven effective in estimating critical shear stress, thus, is applied in the current study. The results demonstrated good agreement ($R^2 = 0.93$) with the measured values. The equation coefficients were modified based on the measured data as Eq. (8):

$$\tau_c = 0.18 \ln \tau_B + 0.01 \quad (8)$$

where τ_c and τ_B are the critical shear stress and yield stress, respectively.

3. Results

3.1. The relation between clay content and critical shear stress

The variation in the critical shear stress of different samples with mud content is shown in Fig. 4(a). The data indicate that in the Chongming samples, as the mud content increased from 10% to 70%, the critical shear stress varied from 0.11 to 0.15 Pa. In the Chongming samples, the critical shear stress increased gradually when the mud content exceeded 30%. The kaolin group exhibited a higher erosion resistance, with a critical shear stress between 0.10 and 0.25 Pa, peaking at 30% mud content before decreasing with increasing mud content. Under certain conditions (e.g., 70%K), the

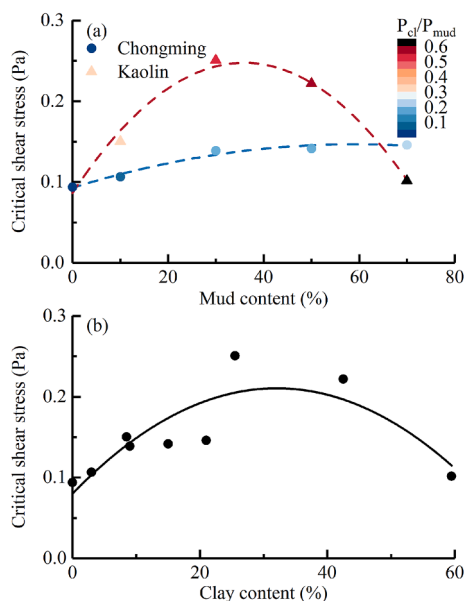


Fig. 4. Critical shear stress for different (a) mud and (b) clay content.

presence of mud can diminish the erosion threshold of the samples.

Given its higher clay content, the kaolin sample had a greater impact on erosion resistance than the Chongming sample, except for samples with a 70% mud content. As seen in Fig. 4(a), for Chongming samples, the clay-to-mud ratio is between 0.07 and 0.2, while for kaolin samples, the ratio is from 0.31 to 0.65. Compared to the mud content, the clay content shows a clear relation with critical shear stress, gradually increasing with clay content and peaking at 30% (Fig. 4(b)). Once the clay content exceeded 30%, the pores in the mixture were filled with clay, and the dry bulk density decreased, resulting in a weakened erosion resistance. With the same mud content, the higher clay content in the kaolin sample enhanced cohesion despite its lower bulk density compared to the Chongming samples. For the kaolin samples, when the mud content reached 70%, the critical shear stress was 0.10 Pa, which was smaller than that of the Chongming sample (Fig. 4(a)). This lower critical shear stress is attributed to the extremely high water content (Table 1), which makes the surface sediment more susceptible to erosion.

3.2. The relation between consolidation degree and critical shear stress

Fig. 5 shows the relation between critical shear stress and consolidation degree for different mud contents, showing that the erosion threshold increases with increasing consolidation. A more consolidated bed has up to 10 times greater erosion resistance than a less consolidated bed. For all sample groups, critical shear stress follows an exponential relation with the consolidation degree. For the 30%CM samples, critical shear stress increased from 0.04 to 1.01 Pa with a corresponding α_c increase from 0.7 to 2.4. For the 70%CM samples, the sediment has a lower consolidation degree, ranging from 0.4 to 2.2, with the critical shear stress between 0.08 and 1.16 Pa. As the consolidation degree increases, the critical shear stress for 70%CM samples shows a steeper trend (Fig. 5). For these samples, the 30%CM sample achieved the highest consolidation state, followed by the 50%CM and 70%CM samples. The higher sand content in the 30%CM sample facilitated a more tightly packed structure, as sand and mud particles were more effectively arranged under the same conditions.

A dimensionless critical shear stress (τ_{cr}/τ_{c0}) was introduced (where τ_{cr} and τ_{c0} denote the critical shear stress of sediment mixtures and pure sand, respectively) to quantify the influence of the consolidation degree. The data from Ye et al. (2011, pp. 973–983) and Smith et al. (2015) were collected to quantify the

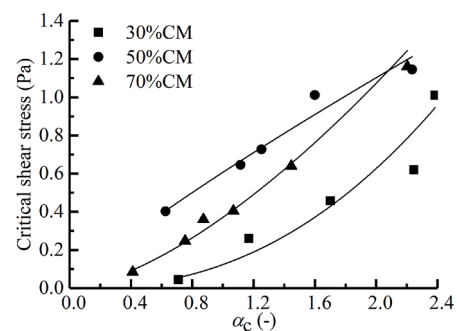


Fig. 5. Critical shear stress under different consolidation degrees.

role of the consolidation degree. As shown in Fig. 6, an exponential function was found between the dimensionless critical shear stress and the consolidation degree, with a correlation coefficient (R)-value of 0.73, which was significant at $P < 0.001$. For this fitting function, when the consolidation coefficient approaches zero, the sample represents a fresh deposit with high erodibility, resulting in minimal critical shear stress.

The three experiments exhibited different trends in response to changes in the consolidation degree, which is ascribed to the clay activity and consolidation methods. For highly consolidated sediment prepared under pressure, such as those in Ye et al. (2011, pp. 973–983), the critical shear stress can reach up to 4 Pa, increasing sharply with the degree of consolidation. In contrast, for moderately consolidated samples, like those in Smith et al. (2015), the critical shear stress shows a more gradual increase. In the current study, the samples with a lower consolidation degree ($\alpha_c < 1.4$), exhibit a slow increase in the critical shear stress, ranging from 0.10 to 0.25 Pa, while the samples with a higher consolidation state ($\alpha_c > 1.4$), show a steeper trend of critical shear stress (Fig. 6). The kaolin samples used in Ye et al. (2011, pp. 973–983) exhibit stronger clay activity and higher cohesive force than Chongming mud in the current study, explaining the differing trends observed at high consolidation degrees ($\alpha_c > 1.4$). For the same samples, changes in the degree of consolidation indicated that the sediment had varying bulk densities, which led to different particle packing states. Different degrees of consolidation also affected the bonding force of the cohesive particles in the sediment structure.

3.3. Erosion equation for sediment mixtures

A multi-factor correlation analysis was done on the current data, and those of Ye et al. (2011, pp. 973–983), and Smith et al. (2015) to explore the crucial physical factors affecting the erosion threshold of sediment mixtures. To assess the degree of correlation between two variables, the Pearson correlation coefficient is applied (Pearson, 1931). The results indicated strong correlations between dimensionless critical shear stress and consolidation degree, solid volume fraction of clay, clay content, and mud content, with corresponding R^2 values of 0.72, 0.63, 0.50, and 0.41, respectively (Table 2). Multiple regression analysis was applied to develop a function for critical shear stress based on these variables. Datasets from previous studies were referenced to test the equation. Due to insufficient data in some studies for coefficient calculation, partial results were selected in Table 3,

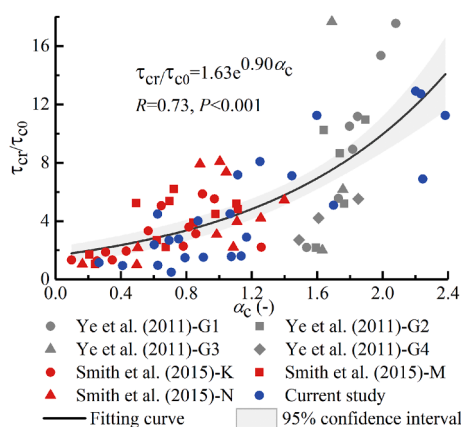


Fig. 6. Relation between dimensionless critical shear stress and the consolidation degree.

including samples with varying degrees of consolidation. Ye et al. (2011, pp. 973–983) did four group experiments with the sand grain size ranging from 159 to 1,332 μm . The groups denoted as G1, G2, G3, and G4 corresponded to median particle sizes of 159, 498, 345, and 1,322 μm , respectively, with varying clay content from 0 to 60%. Smith et al. (2015) used three different muds (kaolinite, abbreviated as K; kaolinite/bentonite, abbreviated as M; Mississippi River field mud, abbreviated as N) in sand-mud mixtures with mud contents ranging from 0 to 100% and clay contents from 0 to 24.5%. In Smith et al. (2015), water content was calculated with the dry and wet bulk density, while the clay and mud content was estimated based on pure mud samples. Since clay content and mud content are highly correlated, and clay content is related to the solid volume fraction of clay, a physically meaningful equation was proposed after numerous trials, incorporating the variables P_m , ϕ_{clay} , and α_c . The critical shear stress of the sediment mixtures can be calculated as Eq. (9):

$$\tau_{\text{cr}}/\tau_{\text{c0}} = c(1 + P_m)^b(1 + \alpha_c)^{e\phi_{\text{clay}}} \quad (9)$$

where $a = 2.41$, $b = 1.10$, $c = 1.17$, and P_m is the mud content. For natural sediment, if the particle size distribution is known, the sand and mud content can be separated to estimate their respective particle sizes. The critical shear stress of pure sand can then be calculated using the Shields criterion (Shields, 1936).

A comparison of the calculated values and measured critical shear stress data is shown in Fig. 7. The equation accurately predicted the critical shear stress for all samples. Out of 77 data points, 76.6% were within the $\pm 50\%$ error margin. The equation overestimated the results collected in the current study because of the higher moisture content of the samples. Among the unconsolidated samples, the surface ones had a higher water content, making them more easily resuspended. In Smith et al. (2015), the critical shear stress was underestimated, owing to the low clay content and the resulting small solid volume fraction of clay. Compared to other equations, the proposed equation accounts for the degree of consolidation, with a simple set of parameters that only include mud content, consolidation degree, and the solid volume fraction of clay. A detailed comparison of the different equation results is given in Section 4.3.

4. Discussion

4.1. Relation between the solid volume fraction of clay and the critical shear stress

Fig. 8 shows the relation between critical shear stress and the solid volume fraction as determined from Eqs. (4)–(6). Compared to the solid volume fraction of mud, the volume fraction of clay exhibited a stronger relationship with critical shear stress (Figs. 8 (a) and (b)). The Kaolin samples exhibited a higher solid volume fraction of clay (0.12–0.23) compared to the Chongming samples

Table 2

The R -values for the Pearson test for critical shear stress and sediment properties.

	$\tau_{\text{cr}}/\tau_{\text{c0}}$	P_{clay}	P_m	ϕ_{clay}	ω	ρ_d
P_{clay}	0.498 ^b					
P_m	0.407 ^b	0.727 ^b				
ϕ_{clay}	0.633 ^b	0.797 ^b	0.397 ^a			
ω	-0.169	0.340 ^a	0.710 ^b	-0.185		
ρ_d	0.116	-0.427 ^b	-0.784 ^b	0.088	-0.922 ^b	
α_c	0.718 ^b	0.356 ^b	0.251 ^a	0.647 ^b	-0.358 ^b	0.384 ^b

^a Indicates significant at $P < 0.05$.

^b Indicates significant at $P < 0.01$. P_m indicates mud content.

Table 3

Summary of datasets from previous studies.

Sand size (μm)	Mud size (μm)	Dry bulk density (kg/m^3)	Critical shear stress (Pa)	Sample preparation	Reference
159, 498, 345, 1,332	1.45	999–1,638	0.22–3.42	8 kPa consolidated 1–2 d	Ye et al. (2011)
5,500 200	16.4 2	1,729–2,551 385–1,573 (calculated)	2.64–21.84 0.22–0.58 (0.25 cm)	100 kPa consolidated 48 h Consolidated 48 h	Gao et al. (2019) Sharif (2003)
353	3.8, 5, 12.7	604–1,459	0.154–2.018	Mud bulk density $1,400 \text{ kg}/\text{m}^3$; consolidated 30 d	Smith et al. (2015)

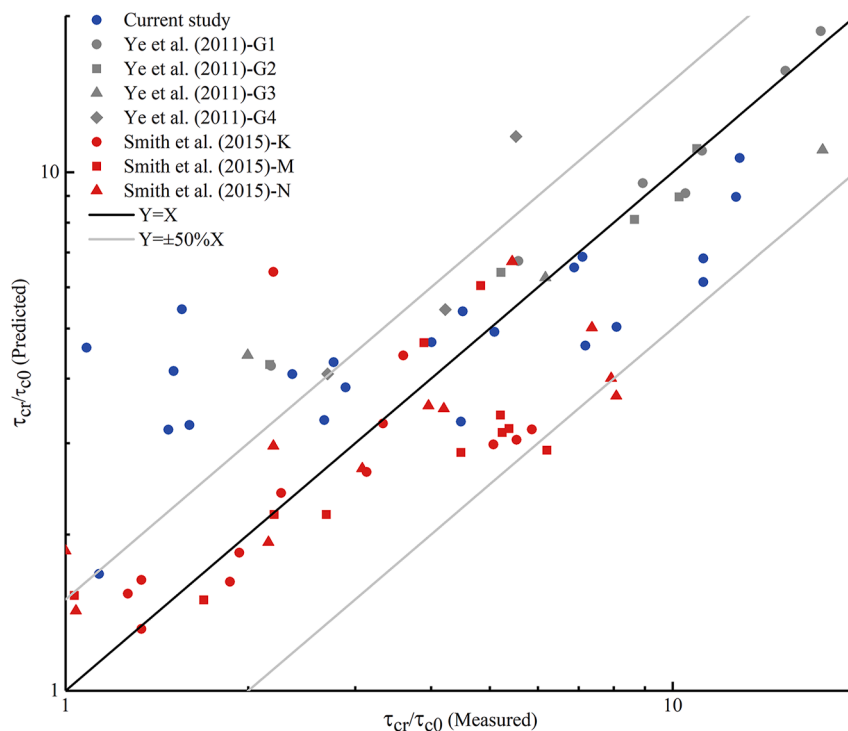
(0.04–0.09), leading to a higher critical shear stress (Fig. 8(a)). The calculated ϕ_{sm} values from Jacobs et al. (2011) and Amos et al. (1997), show a weaker correlation with the erosion threshold compared to ϕ_{clay} (Fig. 8(b)). However, in the samples from Ye et al. (2011, pp. 973–983), the critical shear stress is more strongly correlated with the solid volume fraction of mud. This is ascribed to the higher compaction of the samples, which overwhelms the role of ϕ_{clay} for the compacted samples.

As a function of clay content and water content, ϕ_{clay} represents the relative ratio of clay content to water content in the sediment structures. A larger ϕ_{clay} value indicates either a higher clay content or less water content in the sample. Clay and water content have an important influence on double electric stratification. Clay minerals have small particle sizes and exhibit active electrochemical properties. Clay content is crucial to the cohesion of cohesive sediment structures (Le Hir et al., 2008; van Ledden et al., 2004; van Rijn, 2020a; Yao et al., 2022). An increase in the clay content increases the adhesion force within the sediment, consequently enhancing its erosion resistance (Gong et al., 2021; Huang et al., 2012; van Rijn, 2020a). Changes in water content alter the chemical properties of clay particles, thereby influencing their cohesive force.

The current results suggest that clay particles play a more important role than mud components in the erodibility of sediment mixtures (Fig. 4(a)). Clay particles have a stronger bonding force between particles, which is further influenced by the effect of water content on cohesion performance. Therefore, the solid volume fraction of clay can better represent the cohesive force. ϕ_{sm} serves as an indicator of mud compaction and enables qualitative analysis of cohesive sediment erodibility (Dickhudt et al., 2011). The current results differ from previous studies, which regarded mud dry bulk density as a dominant parameter (Chen et al., 2018; Wu et al., 2018). This overestimates the role of the mud content in sediment mixtures. For a certain ϕ_{sm} , multiple ϕ_{clay} values may exist, leading to more intricate variations in sediment structures. ϕ_{clay} shows better monotonicity and correlation with the critical shear stress, making it a better reference for the empirical equation in sand-mud mixtures.

4.2. Effect of consolidation on sediment mixtures

The erodibility of mud is strongly influenced by the dry/wet bulk density (Houwing, 1999; Krone, 1999). In the experiments, the dry bulk density varied between 400 and $2,400 \text{ kg}/\text{m}^3$ due to varying

**Fig. 7.** Comparison of measured and predicted critical shear stresses for sediment mixtures.

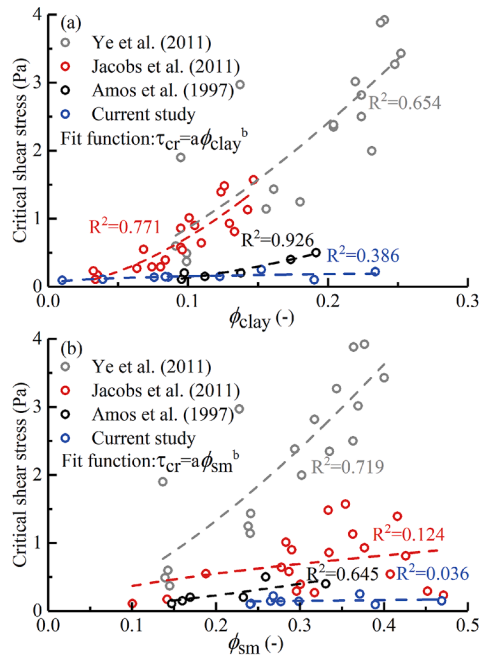


Fig. 8. Relation between critical shear stress and solid volume fraction of (a) clay and (b) mud.

compaction states (Table 3). The samples of Ye et al. (2011, pp. 973–983) and Gao et al. (2019) exhibited a high degree of consolidation with bulk densities from 1,000 to 2,255 kg/m³. In contrast, the results of Sharif (2003), Smith et al. (2015), and the current study revealed a lower consolidation degree, resulting in a dry bulk density range of 385–1,573 kg/m³. For the highly consolidated samples, the critical shear stress reached 20 Pa, whereas for the less consolidated samples, the critical shear stress was usually below 2 Pa (Table 3). Previous studies indicated a strong positive relation between critical shear stress and bulk density for mud (Zhang & Yu, 2017; Zheng & An, 2017). However, no clear relation was found between the two for sand-mud mixtures (Table 2). As mud content increases, critical shear stress rises, while dry bulk density initially increases and then decreases. This creates an ambiguous relation between critical shear stress and dry bulk density across the entire mud content range in mixed sediment.

Different consolidation methods and consolidation times were the main reasons for the difference in the consolidation degree. As indicated in Table 3, the pressurized consolidation process produced the sediment samples with high packing state, even at a high mud content (e.g., samples in Ye et al. (2011, pp. 973–983) and Gao et al. (2019)). This results in a critical shear stress up to 21.84 Pa. However, in the experimental processes described by Sharif (2003) and Smith et al. (2015), the samples were consolidated by their self-weight (Table 3), indicating a lower degree of consolidation. For sediment with consolidation times less than 48 h, the critical shear stress was lower than 1 Pa (Table 3). Critical shear stress shows a significant positive correlation with an increase in consolidation pressure, and erodibility decreases with increased clay content at the same compaction pressure (Kamphuis & Hall, 1983). Under increased pressure, the porosity-mud relation changes (Marion et al., 1992), and sediment particles become densely packed, which influences the porosity structures. Sand particles affect hindered settling and consolidation, causing mud and sand segregation, which complicates the internal structure and impacts bed erodibility.

The solid volume fraction of clay and the degree of consolidation are mutually dependent (Table 2). For samples with a

high consolidation degree, erosion resistance increases more sharply compared to those with a lower consolidation state (Fig. 6). Based on Eq. (9), for sediments with a given mud content, the effect of consolidation degree on critical shear stress depends on the solid volume fraction of clay. As the solid volume fraction of clay is higher, the degree of consolidation exhibits a broader range of variation, resulting in a greater change in critical shear stress.

4.3. Comparison with other equations

To assess the performance of the proposed equation, the developed empirical equation was compared with other equations. Ye et al. (2011, pp. 973–983) introduced a dimensionless critical shear stress based on the experimental results for mixtures of mud with different sand particles, as Eq. (10):

$$\tau_c^* = \frac{\tau_{cr}}{\tau_{sa}} = \frac{c}{1 + e^{-aP_m + b}} \quad (10)$$

where τ_c^* , τ_{cr} , and τ_{sa} , are the dimensionless critical shear stress, critical shear stress of sediment mixtures, and critical shear stress of sand components, respectively; a , b , and c are coefficients related to the sand particle size.

Wang (2013) developed an erosion equation for sediment mixtures that considers the water content and clay content, as Eqs. (11) and (12):

$$\tau_c^* = 8.46 - 27.76w + 73.69P_{clay} + 83.22(w^*P_{clay}) \quad (11)$$

$$\tau_c^* = \frac{\tau_{cr}}{(\gamma_s - \gamma_w)d_{50}} \quad (12)$$

where γ_s and γ_w respectively denote the specific weight of sediment and water. The empirical equations from the current study (Eq. (9)), Wang (2013) (Eqs. (11) and (12)), and Ye et al. (2011, pp. 973–983) (Eq. (10)) were applied to the results of Ye et al. (2011, pp. 973–983), Smith et al. (2015), and those of the current study. As shown in Fig. 9, the equations from Wang (2013) and Ye et al. (2011, pp. 973–983) exhibit significant deviations between the predicted and measured results, typically being applicable only under specific sediment and consolidation conditions. The proposed equation yields more accurate predictions of the critical shear stress for sediment mixtures and can be applied across the full range of mud content and various consolidation degrees. The performances of the different equations were as follows: Eq. (9) (RMSE = 0.62, $R^2 = 0.73$), Wang (2013) (RMSE = 6.82, $R^2 = 0.35$), and Ye et al. (2011, pp. 973–983) (RMSE = 1.24, $R^2 = 0.39$). For Eq. (9), the calculated results deviate from the current experimental data for lower erosion resistance. This discrepancy was attributed to the low degree of consolidation, where a fluffy layer forming on the sediment surface at higher mud content, leading to an underestimation of the erosion thresholds in the current measurements. The equation from Wang (2013) is based on samples with low consolidation and ignores the consolidation degree, occasionally leading to negative critical shear stress values.

Compared to some other theoretical formulas, the proposed equation includes fewer coefficients, accounting for both cohesive forces and gravity in the sediment, making it more practical for application. Moreover, the proposed equation is more convenient for predicting the erodibility of mixed sediment with varying degrees of consolidation. However, the proposed equation, derived from datasets of sand-mud mixtures, is primarily applicable to sediment with a multimodal particle size distribution, such as those in environments influenced by erosion-deposition regime

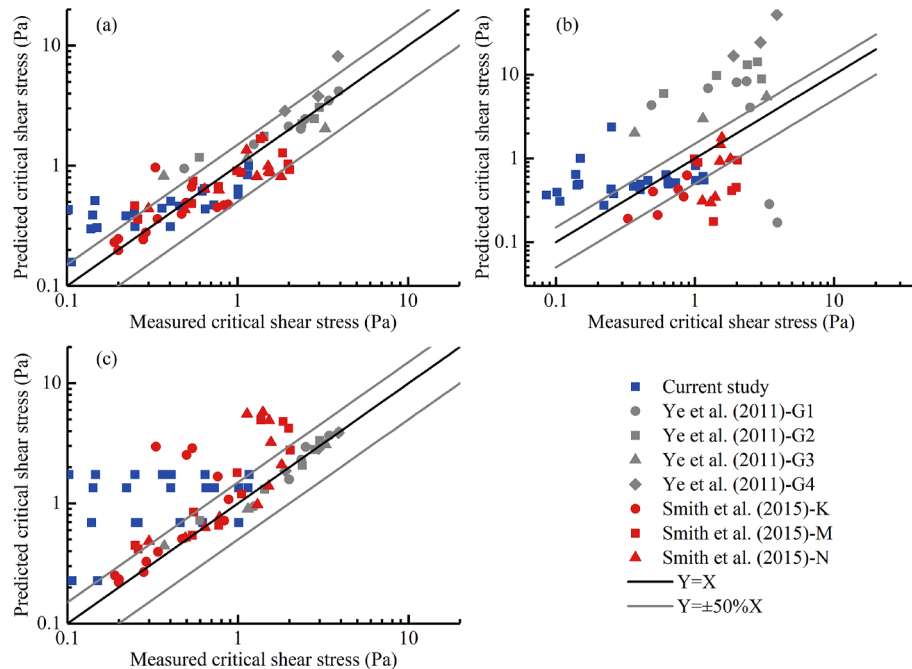


Fig. 9. Comparison of measured critical shear stress and predicted critical shear stress from (a) Eq. (9), and the equations of (b) Wang (2013) and (c) Ye et al. (2011, pp. 973–983).

shifts that alter sediment composition. As the formula was established using sediment with particular properties, such as moderate to high dry bulk density and particle sizes finer than medium-sized sand ($d_{50} < 1,335 \mu\text{m}$), further validation is needed before applying the formula to natural sediments.

In natural sediments containing biological matter, cohesion from substances like Extra polymeric substances (EPS) and bio-films increases the erosion threshold (Fang et al., 2017; Le Hir et al., 2007). Both Smith et al. (2015) and the current study used natural mud samples, ignoring biological matter, which could potentially lead to deviations in the erosion threshold. Additionally, clay mineralogy, water chemistry, and sediment structure, significantly affect erosion strength due to variations in binding capacity and interparticle bonds (Arulanandan, 1975; Kelly & Gularte, 1981; Zreik et al., 1998). Therefore, further studies are required to incorporate these factors and generate more data to assess the applicability of the proposed equation.

5. Conclusions

A series of experiments were done using an annular flume to investigate the erodibility of sand-mud mixtures of sediments with different mud contents. The critical shear stress of the mud-sand sediment mixtures under varying consolidations and the effect of sediment properties were analyzed. The main conclusions are as follows.

- (1) The clay content exerts a significant effect on the erosion resistance of sand-mud mixtures. The critical shear stress increases with rising clay content, peaking at 30%, after which it decreases. Compared to natural mud, kaolin sediment has higher critical shear stress under the same mud content, attributed to the higher solid volume fraction of clay in the kaolin samples, which increases the cohesive force of the sediment matrix.
- (2) The effects of the solid volume fraction of mud (ϕ_{sm}) and solid volume fraction of clay (ϕ_{clay}) on the erosion threshold were compared. ϕ_{clay} , which is an important

indicator of cohesive force for cohesive sediment, has a stronger positive correlation with the erosion threshold of sediment mixtures than ϕ_{sm} .

- (3) The consolidation degree plays a key role in the erosion threshold of mixed sediment. It is suggested that a positive exponential function correlation exists between the critical shear stress and the consolidation degree for sand-mud mixtures with varying mud content. Variations in the consolidation pressures and durations significantly influenced dry bulk density, thereby affecting the critical shear stress of the sediment mixtures.
- (4) The findings of the current study, coupled with data compiled from the literature, were analyzed to define the factors governing the erosion threshold for sediment mixtures. An empirical equation, as a function of mud content, consolidation, and the solid volume fraction of clay was proposed. The new empirical equation, validated with experimental data, accurately predicts the critical shear stress of sediment mixtures in a simple, and more practical form ($\text{RMSE} = 0.62$; $R^2 = 0.73$). This equation is applicable to mixed sediments with medium to high dry bulk density. However, other factors, such as clay mineralogy, pore water chemistry, or biological effects, also affect the erodibility of sediment mixtures, indicating the need for further validation before applying this equation to natural sediment.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that may have influenced the work reported in this study.

CRedit authorship contribution statement

Zhonghao Zhao: Writing – original draft, Visualization, Validation, Methodology, Data curation. **Yuan Xu:** Resources, Methodology. **Xianye Wang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Jianwei Sun: Writing – review & editing, Visualization, Methodology, Formal analysis. **Qing He:** Supervision, Resources, Project administration, Funding acquisition.

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