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ORIGINAL ARTICLE

Morphological characterization of suspended particles under wind-induced disturbance in Taihu Lake, China

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Abstract Sediments are disturbed by wind frequently, especially in the shallow lakes. The characteristics of resuspended sediment particles in Taihu Lake were studied under different wind velocities. It showed that sediment particles suspended obviously and particle number in overlying water increased directly under high wind-induced disturbance. Suspended solid (SS) concentration was less than 50 mg/l when the wind velocity was below 3.0 m/s, however, it increased to more than 300 mg/l when the wind velocity was 10.0 m/s. Two methods were used to measure the fractal characteristics of particles. One was light scattering and the other was image analysis. The three-dimensional fractal dimensions of suspended particles, measured by light scattering, were between 2.26 and 2.44; correspondingly, the two-dimensional fractal dimensions, calculated by image analysis, were between 1.44 and 1.77. Moreover, the three-dimensional fractal dimensions were directly proportional to two-dimensional fractal dimensions. The characteristic length of particles was calculated by image analysis. The minimum characteristic length was close to 8.5 μm when the wind velocity was 1.5 m/s at 50 cm beneath lake surface, while, the maximum characteristic length was approximate to 24 μm when the wind velocity was 10 m/s at the depth of 150 cm.

Keywords Sediment Particles · Resuspension · Morphology · Wind · Fractal Dimension · Taihu Lake

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1 Introduction

The interface between sediments and overlying water is not steady. Disturbing shear-force by wind influences the interface frequently. As a result, the sediment particles resuspended, and the steady interface is destroyed. Resuspension of lake sediments is a function of the bottom shear stress as the result of fluid motion and the local sediment characteristics (Håkanson and Jansson, 1983; Blom *et al.*, 1992). Although several hydrodynamic processes can intervene on sediment resuspension, wind-induced waves are usually the dominant process in shallow lakes (Leuttich *et al.*, 1990; Weyhenmeyer *et al.*, 1997; Douglas and Rippey, 2000). Resuspension of unconsolidated surface sediments in shallow lakes during periods of heavy wind can result in high levels of turbidity and nutrients in the overlying water and as an environmental perturbation plays a significant role in geochemical, toxicological and biological processes. Due to its multiple effects on the ecosystem of lake, there has been increased awareness of the importance of the resuspension process in shallow lakes. In recent years, the influence of sediments resuspension on lake ecological system was studied by significant number of researchers (Michelcic *et al.*, 1996; Pejrup *et al.*, 1996; Rutgers *et al.*, 1997). Special attention was paid to shallow lake, because the sediments of shallow lake were disturbed by wind and the resuspension happened more frequently (Hawley and Lesht, 1992; Søndergaard *et al.*, 1992). Qin *et al.* (2003) analyzed the influence of wave and current of Taihu Lake on sediments suspension, and demonstrated that the sediments suspended extensively when wind velocity was above 6.5 m/s. Zhu *et al.* (2005) researched on the resuspension of sediment particles under different wave intensity by flume experiments.

Under the wind-induced waves, particles on the surface of sediments swarm into overlying water. During the resuspension, there are lots of aggregates formed by flocculation, collision, and breakage. Generally, the aggregates formed by suspended particles are not spherical particles, but are irregular fractal aggregates, and thus fractal characteristics play an important role in the behavior of aggregated particles. In recent years, irregular aggregate shapes have been described in terms of fractal geometry concepts, and complete characterization of particles suspension should include a description of the fractal dimension of the aggregates (Jiang and Logan, 1991; Johnson *et al.*, 1996). Li *et al.* (1998) calculated the fractal dimensions of small particles in Eastern Pacific coastal waters and indicated that fractal dimensions was highest ($D_f = 2.59$) in East Sound during a phytoplankton bloom, and lowest ($D_f = 1.77$) at one site in Monterey Bay where old diatom flocs and marine snow-size aggregates. Logan and Wilkinson (1990) analyzed the size-porosity correlations for two types of marine snow aggregates yielded fractal dimension s of 1.39 and 1.52.

The importance for measurements of geometry of particles has long been recognized in the chemical, biological, and other process industries. Since sediment particles are fractal, their properties, such as density and settling velocity, are non-Euclidean functions of size, while geometrically defined shapes such as cubes and spheres scale according to their sizes raised to integer powers, fractal objects scale according to fractal powers. The properties of fractal aggregates can be derived from aggregate parameters that include shape factors, packing factors and fractal dimensions.

Fractal geometry concepts are useful in describing the rugged surface of large, irregular, porous aggregates that are not well defined by Euclidean geometry. Since Mandelbrot introduced the concept of fractal theory in the 1970s, the application of fractal geometry is now a well-established means of describing the complicated structure of aggregates (Gregory, 1998; Tang, 1999; Watie *et al.*, 2001; Bushell, Yan, Woodfield, Raper, & Amal, 2002; Wu *et al.*, 2002). Mass fractals may be summarized by the relationship between their mass M, a characteristic measure of size L, and the mass fractal dimension D_f:

$$M \propto L^{D_f} \tag{1}$$

For Euclidean objects, the value of D_f will be 1 for a line, 2 for a two-dimensional planar shape, and 3 for a compact three-dimensional shape (Waite, 1999). Fractal objects take noninteger values of D_f and are have non-Euclidean dimensionality. Densely packed aggregates have a high fractal dimension, while lower fractal dimension results from large, highly branched and loosely bound structures.

Experimental measurement of fractal dimensions of real aggregates is not straightforward, and the methods available are almost indirect. At present, there is no established method for predicting the values of these parameters for aggregates formed by suspended sediment particles in the shallow lakes, meanwhile, limited information is available in literature about the morphological characteristics of particles resuspended by wind-induced disturbance in shallow lakes. In order to gain further insight into the characteristics of resuspended particles in shallow lakes, a series of studies were carried out on the resuspended particles under wind disturbing conditions in Taihu Lake.

2 Study area

Taihu Lake located in the center of the Yangtze River Delta, one of the most developed economic zones eastern China, is the third largest fresh water lake in China. It is a large and typical shallow lake with an area of 2338 km^2 and an annual average water depth of 2 m.

Fig. 1 The map of Taihu Lake and the sampling location

Taihu is a necessary water resource for agriculture, industry and drinking water of the Yangtze River Delta. It plays an extremely important role in the area for economical and social development (Hu *et al.*, 2006). An increasing amount of pollutants, however, has been discharged into the lake directly and indirectly due to the economical and social development. Consequently, the lake ecosystem has deteriorated. The resuspension of sediments in Taihu Lake plays a pivotal role on ecological system, meanwhile, the wind-induced disturbance influences the sediments suspension significantly.

The system studies are located in the northern part of Taihu lake and the site was called Td (31°25′10″N, 120°12′50″E) (Fig. 1). Distance between Td position and bank of the lake is about 100 m, and the average water depth of Td position is 1.9 m.

3 Materials and methods

The period of this study was from 8 to 12 April 2005. During the five days, wind velocity changed obviously and was recorded every hour. The overlying water was sampled on different time, 4-8-12 (represented 12 o'clock at 8 April), 4-9-18, 4-11-8, 4-12-8 and 4-12-17, meantime, the samples with suspended particles were also collected on 0.5 m, 1.0 m and 1.5 m depth under water surface. The samples were transported to the laboratory immediately, and then suspended solid concentration and morphological characteristics were measured. The laboratory was on the bank and about 100 m apart from Td location. The suspended solid concentration was measured by Portable Datalogging Spectrophotometer (DR/2010, Hach, USA).

In this paper, we used image analysis to calculate the two-dimensional fractal dimensions, and used light scattering to determine the three-dimensional fractal dimensions.

3.1 Image analysis

The two-dimensional fractal dimension is defined by a power law relation between projected area (A) and the characteristic length of the aggregates, l.

$$A \sim l^{D_2} \tag{2}$$

where D_2 is the two-dimensional fractal dimension (Kilps *et al.*, 1994; Chakraborti, Atkinson, & Van Benschoten, 2002).

3.2 Light scattering

During light scattering, a light beam is passed through a sample. The particles in the sample scatter light proportionally to their size and at a constant angle independent of which part of the particle is hit by the beam. Small particles scatter light at high angles, while large particles scatter at lower angles. In light scattering study, the scattered intensity as a function of the magnitude of the scattering wave vector, Q, is measured, where,

$$Q = \frac{4\pi n \, \sin(\theta/2)}{\lambda} \tag{3}$$

In this equation, n, θ, and λ are the refractive index of the medium, the scattered angle, and the wavelength of radiation in vacuum, respectively (Wu *et al.*, 2002). It has been shown that for a mass fractal aggregate, which satisfies the conditions for Rayleigh-Gans-Debye (RGD) regime, its scattered intensity I is described by the following equation (Biggs *et al.*, 2000).

$$I \propto Q^{-D_f} \tag{4}$$

So, on a log-log plot there should be a liner region, with a slope of $-D_f$. This method has been widely used, even in the cases where the RGD approximation would not be expected to apply.

Image analysis of suspended particles was operated by microscope with high solution CCD camera (B2 series system microscopes, Motic Incorporation, USA). A small amount of the suspension was gently collected from the sampling bottle using a glass tube of 5 mm inner diameter, and then was moved to a cell mounted on the microscopic camera for image analysis of the particles in the suspension. Because the sampling tube was sufficiently large and the cell was previously filled with an amount of deionized water, no breakage or further growth occurred with the sampled particles during image analysis under operation with care. The pictures of suspended particles were captured by CCD camera and then were analyzed by image analysis software (Mivnt, DaHeng, China). In this work, the long axis of the fitted ellipse, which is fitted to the particles image such that the moment of inertia of the ellipse and the image are equal, was taken as the characteristic length. The two-dimensional fractal dimension was calculated by regression analysis of the logarithm of the projected area versus the logarithm of the long axis of the fitted ellipse as suggested by eq. 2. Meanwhile, a laser diffraction instrument (Mastersize, 2000; Malvern, UK) worked as the light scattering for three-dimensional fractal dimension calculation.

4 Results and discussion

4.1 Wind velocity

The variation of wind velocity was shown in Fig. 2. At the beginning, there was only low wind velocity and the velocity was close to 2.0∼4.0 m/s and was 3.0 m/s at 4-8-12. The low wind velocity had maintained for 48 h, thus, the lake was correspondingly stable during this period. After that, heavy wind happened and the maximum wind velocity was above 11 m/s and the wind velocity was 10.0 m/s at 4-9-18, at this time, the sediments were disturbed observably, meanwhile, the transparency of the overlying water decreased sharply. This heavy wind continued about for 24 hrs, after that, wind velocity decreased to 1.5∼3.0 m/s sequentially. At 4-11-8, the wind velocity was 1.5 m/s, which was the lowest value during the five days study, at this time, lake was disturbed slightly and this condition could be regarded as comparative static state. At the end, the wind velocity increased gradually after 4-11-8, when at 4-12-8 and 4-12-17, the wind velocity grew up to 6.0 and 7.0 m/s respectively. The five sampling times and their wind velocity were listed in the Table 1.

4.2 Suspended solid (SS) concentration

The SS of overlying water on different depths was shown in Fig. 3. At 4-8-12, SS was below 20 mg/l

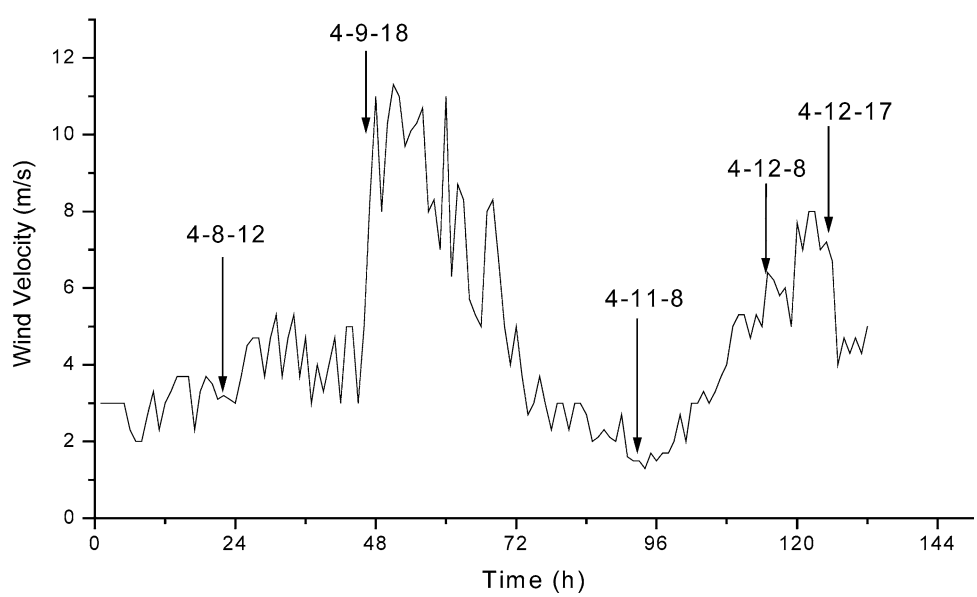

Fig. 2 The curve of wind velocity changing with time

Table 1 Wind velocity at five sampling time

Time	Wind velocity (m/s)
4-8-12	3.0
4-9-18	10.0
4-11-8	1.5
4-12-8	6.0
4-12-17	7.0

at all of the depths, as a result of the low wind velocity of 3.0 m/s. The results showed that the long time weak wind intensity could not disturb the sediments observably and the sediment particles didn't suspend adequately, thus, the particle number in suspension was almost uniform and there was no discriminating of the solid concentration at different depths. It was also noticed that SS at 50 cm was slightly higher than that at the other depths of 4-8-12. Since there were more suspended particles with lower density in 50 cm. At 4-9-18, the wind velocity was 10.0 m/s, and the sediments were sheared sufficiently. A great deal of sediment particles resuspended into the overlying water, therefore, SS increased sharply. But there were obviously different SS concentrations on the three depths. It was noted that 4-9-18 was at the beginning of heavy wind occurrence, thus, a majority of resuspended particles were still close to the surface of sediments and these particles diffused to water gradually, moreover, particles had not diffused equably on vertical direction. So that SS was about 100 mg/l at 50 cm, 220 mg/l at 100 cm and 340 mg/l at 150 cm. Furthermore, SS on 150 cm was three times higher than which at 50 cm. After the period of heavy wind, there was gradually decreasing wind intensity. During the decrease of wind velocity, the resuspended particles precipitated to the bottom again; therefore, the SS concentration of 4-11-8, with 1.5 m/s wind velocity, was reduced rapidly to 30 mg/l. Although the wind disturbing intensity at 4-11-8 was lower than that at 4-8-12, the SS concentration was higher than the former. In view of the fact, there were more particles at 4-11-8 resuspended by the former high wind intensity and lots of particles with low density, precipitating to the bottom difficultly, were still on the overlying water. After the static condition at 4-11-8, the wind velocity increased with time and the SS concentration increased again. When at 4-12-8, the SS concentration was only slightly higher than that at 4-11-8, but the SS concentration of 4-12-17 was higher than that at 4-11-8 remarkably. It has been pointed out that 4-12-8 was 24 hrs after 4-11-8 and the wind velocity increased from 1.5 m/s to 6.0 m/s gradually, thus, the particles of surface sediments resuspended step by step and most of the resuspended particles were which precipitated to bottom at the period of 4-11-8. While, there were 9 hrs between 4-12-8 and 4-12-17, and the wind velocity was close to 6.0 m/s during the 9 hrs, thus, not only the particles of surface sediments resuspended to the overlying water, but also deeper sediments particles could be suspended by the long time wind disturbance. So that SS of 4-12-17 approached to 180 mg/l, comparatively, SS of 4-12-8

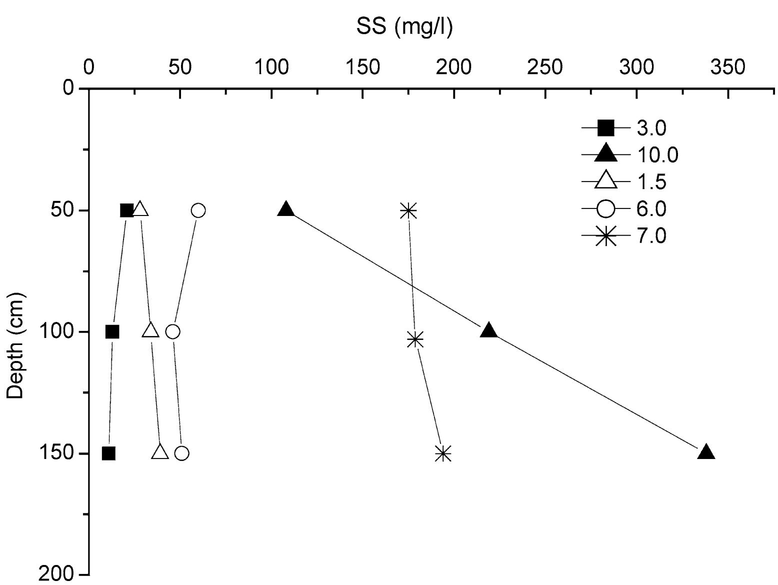

Fig. 3 Concentration of suspended solid on different depth under various wind velocity

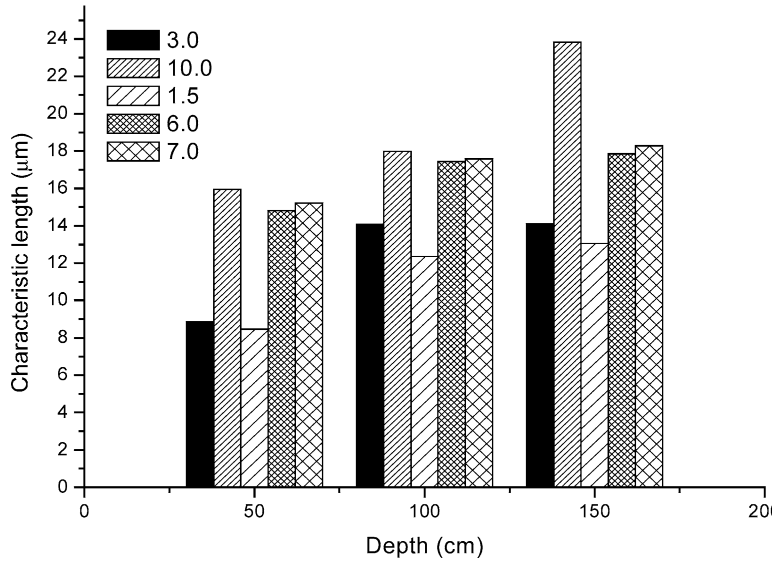

Fig. 4 Characteristic length of suspended particles on different depth under various wind velocity

was close to 50 mg/l and was slightly higher than that of 4-11-8.

4.3 Characteristic length of suspended particles

The variation of characteristic length of suspended particles on different depths under wind-induced disturbance was presented in Fig. 4. In general terms, the characteristic length of 150 cm was higher than those at 50 cm and 100 cm, due to the number of particles in suspension at 150 cm was more, thus, the opportunities for suspended particles aggregating to larger ones were more frequent. From Fig. 4, it can be seen that the characteristic length varied with the change of wind velocity, furthermore, the characteristic length increased with a rise of wind velocity. The minimum characteristic length was close to 8.5 μm when the wind velocity was 1.5 m/s at 50 cm, while, the maximum characteristic length was approximate to 24 μm when wind velocity was 10 m/s at 150 cm. Comparing wind velocity of 3.0 m/s with 1.5 m/s, it was found that the rule of characteristic length was in conflict with which of SS concentration, because SS concentration was higher in 1.5 m/s wind, but the characteristic length was higher in 3.0 m/s wind. Since the 1.5 m/s wind followed heavy wind of 10.0 m/s, more particles with lower density suspended, meanwhile, which were smaller and difficult to precipitate, thus, SS was higher in 1.5 m/s wind but the characteristic length was lower in 1.5 m/s wind.

4.4 Morphological characteristics of suspended particles

Image analysis was used to calculate the two-dimensional fractal dimension. Meanwhile, light scattering was used to determine the three-dimensional fractal dimension. It can be seen from Table 2 that the range of three-dimensional fractal dimensions were from 2.26 to 2.44 and the two-dimensional fractal dimensions were from 1.44 to 1.77, thus, the true dimensions of suspended particles were noninteger values and it turned out that the particles in suspension were non-Euclidean dimensional shapes. Moreover, the fractal dimensions measured by light scattering were directly proportional to that calculated by image analysis.

At 4-8-12, the fractal dimensions on different depths were very close and the values were highest among five different wind intensities. It should be pointed out that the wind velocity changed slightly during the period of 4-8-12, thus the disturbance on particles was steady, meanwhile, the particles could be flocculated into denser aggregates. When the wind velocity grew up to 10 m/s, the sediments were disturbed intensely and the number of particles suspending to overlying water increased obviously, thus, the probability for collision between particles enhanced, so that larger aggregates with lower density and more porosity were formed. The largest characteristic length and the lower values of fractal dimension synchronously occurred at 4-9-18. After the period of heavy wind, there was

Table 2 Fractal dimensions of suspended particles on different depth under various wind velocity

			Light-scattering		Image analysis		
Time	Wind velocity (m/s)	Depth (cm)	Fractal dimension (D_3)	R^2	Fractal dimension (D_2)	R^2	L/S ratio
4-8-12	3.0	50	2.44	0.9984	1.77	0.87	1.75
		100	2.43	0.9986	1.75	0.88	1.62
		150	2.42	0.9976	1.75	0.91	1.53
4-9-18	10.0	50	2.31	0.9996	1.60	0.90	1.53
		100	2.29	0.9996	1.56	0.83	1.65
		150	2.29	0.9996	1.52	0.95	1.49
4-11-8	1.5	50	2.26	0.9948	1.44	0.93	1.65
		100	2.34	0.9973	1.65	0.94	1.64
		150	2.33	0.9977	1.62	0.96	1.48
4-12-8	6.0	50	2.38	0.9984	1.68	0.93	1.52
		100	2.35	0.9995	1.65	0.81	1.85
		150	2.36	0.9996	1.65	0.89	1.77
4-12-17	7.0	50	2.32	0.9991	1.61	0.93	1.52
		100	2.33	0.9992	1.65	0.85	1.66
		150	2.35	0.9994	1.70	0.88	1.62

a correspondingly static state with 1.5 m/s wind at 4-11-8. As mentioned above, there were many aggregates with low density and small size remained in the overlying water, especially at 50 cm depth, while, the aggregates with high density precipitated to the deep, therefore, the fractal dimensions at 50 cm of 4-11-8 was minimum, the three-dimensional fractal dimension was 2.26 and the two-dimensional fractal dimension was 1.44. Moreover, the fractal dimensions of 50 cm were less than that of 100 cm and 150 cm at 4-11-8. When wind velocity increased to 6.0 and 7.0 m/s, the fractal dimensions kept on 2.32–2.36 for three-dimensional and 1.64–1.68 for two-dimensional respectively.

The ratio of the long axis to short axis of the fitted ellipse was between 1.48 and 1.77, the result also showed that the suspended particles were not ascribed

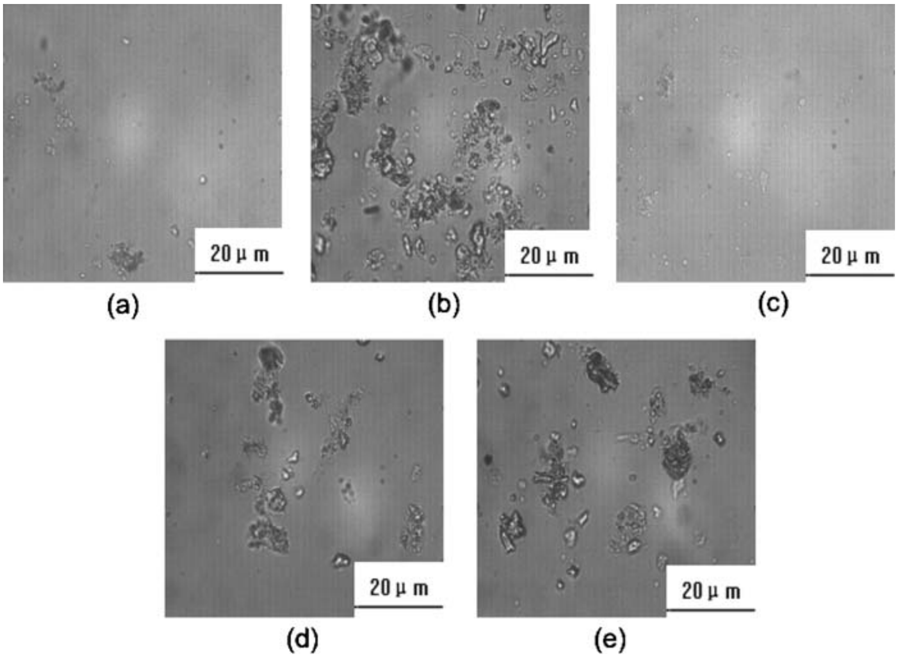

Fig. 5 The microscopic image of suspended particles on 100 cm depth under different wind velocity. Wind velocity is (a) 3.0 m/s; (b) 10.0 m/s; (c) 1.5 m/s; (d) 6.0 m/s; (e) 7.0 m/s

to sphere of Euclidean geometry, they were irregular fractal aggregates. For instance, the microscopic images of suspended particles on 100 cm depth under different wind velocity were shown in Fig. 5, the true shape of the particles was irregular, moreover, the number of the particles increased with the increasing of wind velocity.

5 Conclusion

The resuspension of sediment particles in shallow lakes is significantly influenced by hydrodynamic disturbance. Those processes play an important role in water system. When there is high wind-induced disturbance, the sediment particles suspended obviously and the particles number in overlying water increases directly. Meanwhile, the suspended particles do not belong to sphere of Euclidean geometry, they are irregular fractal aggregates, and thus, characterization of particles in suspension should include a description of the fractal dimension of the aggregates.

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