Coagulation and sedimentation of particulate pollutants in marine waters after wastewater outfall discharge

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Abstract Outfall discharge to seawater is generally used as a practical means of wastewater disposal in many coastal cities. However, deposition of solid pollutants from the wastewater on the seabed would affect the benthic communities. In the present study, both laboratory experiments and numerical simulations were carried out on the role of particle coagulation in the transport and sedimentation of sewage solid materials in marine waters after outfall discharge. Actual sewage samples were collected from two treatment plants in Hong Kong for the experimental study. A flocculator-imaging system was developed for characterization of the particle size distribution (PSD) dynamics during flocculation and dilution of sewage particles in seawater. The system consisted of an external flow-through cell, a microscopic CCD video recorder and an image analyzer. The laboratory results demonstrated that coagulation played an important role in regulating the transport of solid pollutants in marine waters. Flocculation of 30–45 min could shift the PSD considerably, transforming small particles to larger, fast-settling particle aggregates. With a growth in particle size by flocculation, the average settling velocity of the sewage particulates increased by a factor of 2 or more. In addition to the laboratory study, a mathematical model was developed to simulate the transport dynamic of wastewater particles in seawater after outfall discharge. The results of numerical simulations compared well with the experimental observations. Both laboratory and simulation results suggest the important role of coagulation in the transport and sedimentation dynamics of sewage particles in marine waters, especially in the early phase of outfall discharge. As a result, suspended solids from the wastewater discharge would deposit more closely in the vicinity of the outfall sites.

Keywords Coagulation; flocculation; numerical simulation; outfall; particle; sedimentation; sewage

Introduction

In many coastal cities, wastewater is discharged through oceanic outfalls into marine waters after various forms of land-based treatment. In developed countries with relatively high environmental expectation, normally secondary wastewater treatment would be provided. However, for developing countries, marine discharge of wastewater after only primary sedimentation or even a lower level of treatment is still practiced in locations with good tidal current and flushing. Since the solid matter in sewage contains the majority of heavy metals and organic pollutants, marine discharge of less-treated sewage could affect the sediment compositions on the seabed. There is a need to understand the transport dynamics of sewage particles in marine water so as to assess and control the impact of discharged suspended solids on the benthic environment.

Coagulation and flocculation may play an important role in the transport of sewage particles since this process transforms small particles into larger particle aggregates and thus alters the settling rate of solid matter (Jackson and Lochmann, 1993; Alldredge *et al.*, 1995; Li and Logan, 1995). The coagulation kinetics, however, are difficult to predict due to the complex physical and chemical mechanisms involved, a wide range of particle sizes and the fractal structure of particle aggregates. Particle coagulation has not been

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considered in outfall plume models to describe the early mixing and intermediate transport. The role of particle coagulation in the transport of discharged particles in seawater as well as their deposition on the seabed remains to be determined through both theoretical and experimental studies.

In this study, laboratory experiments were carried out using a flocculator-imaging system to determine the importance of coagulation in the evolution of the size distribution of sewage particles in marine waters. The experiments were designed to simulate the particle dynamics in seawater during the early wastewater outfall release. The average settling velocities of the particulate matter after various coagulation periods were measured with a specific settling column. Numerical models were also developed using a recently proposed fractal-curvilinear coagulation kernel that included the usage of a continuous size density function, the applications of a comprehensive curvilinear model and the fractal scaling relationship for particle aggregates.

Materials and methods

Theory

Particle coagulation kinetics. The coagulation dynamics of the sewage particles mixing with seawater can be modeled by the change in particle size distribution (PSD) (Jackson and Lochmann, 1993; Li and Zhang, 2003), i.e.,

$$\frac{dn(m)}{dt} = \frac{1}{2}\int_0^m \alpha\beta(m - m', m')n(m - m')n(m')dm' - n(m)\int_0^\infty \alpha\beta(m, m')n(m')dm' + \varphi n(m) \quad (1)$$

where t is time, $n(m)$ is the particle size density function with respect to the mass, m, β is the collision frequency function, α is the collision efficiency between particles, and m' is the mass of a particle smaller than m, φ is the specific dilution rate of the sewage particles mixing in the seawater. Equation (1) can be solved using the numerical technique with the sectional approximation (Jackson and Lochmann, 1993; Zhang and Li, 2003; Li *et al.*, 2004).

Coagulation kernels particles in water are brought into contact by three different collision mechanisms. According to the rectilinear model, there are the following formulations for collisions between two particles i and j:

Brownian motion

$$\beta_{Br}(i,j) = \frac{2kT}{3\mu}\left(\frac{1}{l_i} + \frac{1}{l_j}\right)\left(l_i + l_j\right)$$

fluid shear

$$\beta_{Sh}(i,j) = \frac{G}{6}\left(l_i + l_j\right)^3$$

differential sedimentation

$$\beta_{DS}(i,j) = \frac{\pi}{4}\left(l_i + l_j\right)^2\left|U_i - U_j\right|$$

where l is the size of the particles indicated, k is Boltzmann's constant, T is the absolute temperature, μ is the fluid viscosity, G is the shear rate, and U is the settling velocity of the particles concerned. Curvilinear models that take into account the hydrodynamic interactions between approaching particles are more accurate than the rectilinear model for the description of particle collision kinetics. Based on a comprehensive numerical solution provided by Han and Lawler (1992), the curvilinear β_{cur} can be related to the rectilinear β by

$$\beta_{cur}(i,j) = e_{Br}\beta_{Br}(i,j) + e_{Sh}\beta_{Sh}(i,j) + e_{DS}\beta_{DS}(i,j) \tag{2}$$

where e_{Br}, e_{Sh}, and e_{DS} are the curvilinear reduction factors for the three collision mechanisms (Han and Lawler, 1992; Li and Zhang, 2003).

Fractal aggregates and their settling velocities. Aggregates of sewage particles are highly porous and irregular in shape, and can be characterized as fractals (Li and Logan, 1995). For fractal aggregates, their masses and lengths can be related according to $m \sim l^D$, where D is the fractal dimension. The settling velocity of a particle aggregate can be calculated using Stokes' law,

$$U = \frac{g(\rho_a - \rho_l)l^2}{18\mu}, \text{ or } U = \frac{g(\rho_p - \rho_w)m}{3\pi\mu\rho_w l} \tag{3}$$

where ρ_p and ρ_w are the densities of the particulate matter and seawater respectively.

Experiment

Flocculation experiments. Coagulation of sewage particles during the initial mixing and dilution in seawater after outfall discharge were experimented in a flocculator (Figure 1). The flocculator was a cylindrical vessel having a diameter of 12 cm and a depth of 15 cm. It was made of acrylic with a 10 cm deep cone bottom. An external recirculation line with an observatory cuvette was connected to the flocculator. The vessel was initially filled with a 1.5 L sewage sample that was mixed by a 3-blade compeller installed 3 cm above the

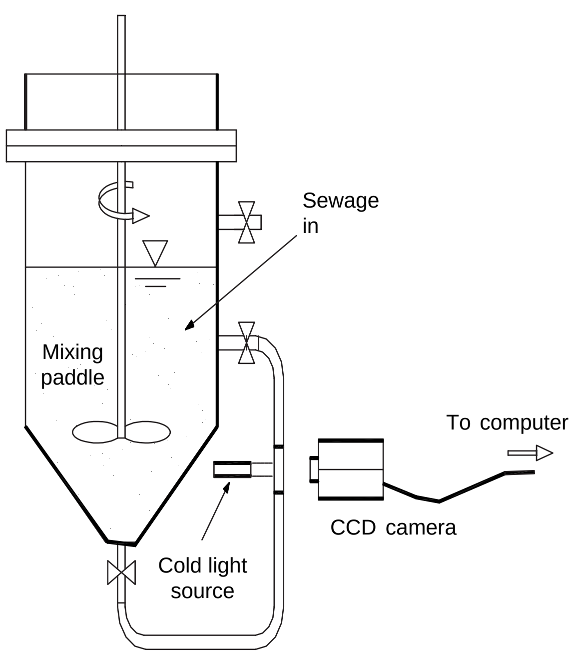

Figure 1 Schematic diagram of the flocculator-imaging system for PSD characterization

bottom, which generated an uplifting flow through the center of the vessel. In order to record the PSD dynamics during the flocculation process, a flocculator-imaging system was developed. The imaging system consisted of a CCD camera (WAT-90251, Watec) with lighting and an image acquisition and analysis system (AnalySIS® 3.1, Soft Imaging System). During a flocculation experiment, the particle suspension in the flocculator was forced by the compeller to flow through the recirculation tube. The CCD camera with a × 10 microscopic lens and a resolution of 576 × 768 was placed facing the cuvette to record the projected images of the particles in the suspension. Particles in the flow through the cuvette were front-lit by a cold light source (L-150, μ-image, Chinetek) for video recording. The image system with a frame grabber took 20 digital photos per min for the PSD determination. The photographic images were analyzed by the image software for particle sizing and counting, following procedures that are detailed elsewhere (Li and Logan, 1995; Zhang and Li, 2003). Twenty consecutive images were analyzed to produce a size distribution of the particles in a range of 2 to about 1,000 μm after a specific time interval of flocculation.

Two sewage samples for the experimental study were collected from local wastewater treatment plants of Hong Kong: one from the Stonecutters Island Sewage Treatment Works (SCI STW) and another from the Stanley Sewage Treatment Works (Stanley STW). During a flocculation experiment, screened seawater was pumped into the flocculator continuously at a pre-determined flow rate to simulate the dilution of the sewage in seawater after outfall discharge. Overflow of the sewage–seawater mixture was allowed to maintain a consistent water level in the flocculator. The dilution rate was set so that it gave a dilution factor of 5 times in 45 minutes. The shear rate used for the laboratory study was $5\,s^{-1}$.

Average settling velocity of particle settling velocity measuring. In measuring the average settling velocity of the particles after a period of coagulation, the water sample of around 100 mL was collected from the flocculator and placed in a 100 mL graduated volumetric cylinder with an effective sectional area of $5.0\,cm^2$. The sedimentation flux of the solid materials within 30 min, F, could be determined. The average settling velocity of the solid matter was calculated by $U = F/C$, where C is the concentration of suspended solids (SS) in the water sample.

Results and discussion

Evolution of the size distribution of sewage particles during flocculation in seawater

The changes of the size distributions of sewage particles during flocculation and dilution in the flocculator were plotted in terms of the particle mass concentration against a series of sizes (Figures 2 and 3). The flocculation dynamics were also simulated numerically for the sewage particles under similar mixing, dilution and coagulation conditions. From the simulation, the PSD of sewage particles discharged into seawater was unimodal in shape with a particle size corresponding to the peak particle mass concentration. The simulation results compared reasonably well with the experimental observations. The PSD evolution demonstrated by both the laboratory study and mathematical simulations suggested an important role of coagulation in the transport of solid pollutants in ocean after the outfall discharge. Flocculation joined small particles together to form larger aggregates, which shifted the PSD from the sizes of small particles to those of larger ones. Meanwhile, the dilution factor decreased the concentration of all particles with time. Nonetheless, the peak size of the PSD increased rapidly in the early mixing phase after sewage discharging into seawater. The particles then grew slowly in size in the late phase of sewage discharge and mixing. According to the experiment for the SCI sewage particles, the peak

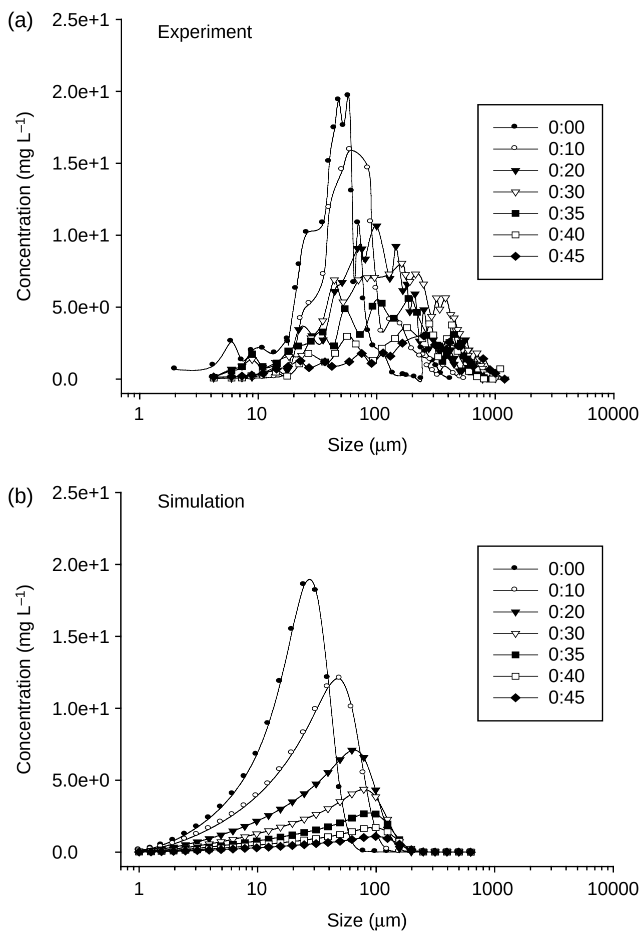

Figure 2 Evolution of the sewage PSD in seawater during flocculation for the sewage sample collected from SCI STW: (a) experimental observation and (b) numerical simulation

concentration decreased from 20.1 to 2.2 mg/L, while the corresponding peak size increased from 40 to 300 μm. Based on the numerical simulation, the peak concentration decreased from 19.8 to 1.5 mg/L, while the corresponding peak size increased from 35 to 120 μm. For the Stanley sewage particles, the peak concentration decreased from 20.1 to 2.5 mg/L according to the experiment and from 20.0 to 1.3 mg/L according to the simulation. The peak size increased from 45 to 600 μm during the experiment and from 35 to 250 μm in simulation. The results demonstrated that coagulation increased the size of sewage particles significantly in the early phase of marine outfall discharge. The sewage particle flocculation dynamics can be well simulated using the models developed in this study.

Change of particle settling velocities

Change in the average settling velocity of the sewage particles during coagulation was investigated through both experimental measurement and numerical simulation (Figure 4). From the observation, two stages of settling velocity increase could be identified. For the sewage samples taken from the SCI STW, the average settling velocity of solid materials increased from the initial value of 2.6 to 4.8 m/d after 35 min of coagulation. Afterward, there was little increase in settling velocity. For the sewage taken from the Stanley STW,

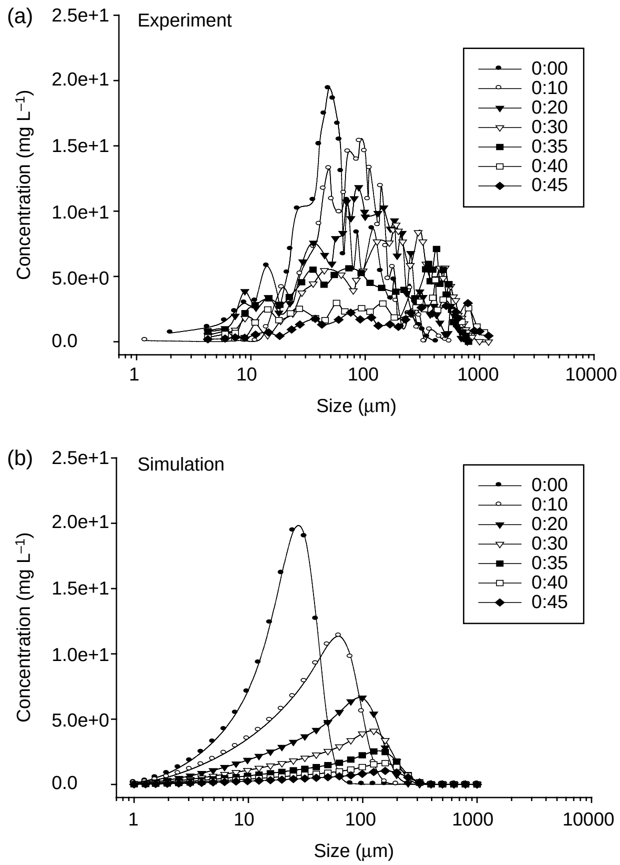

Figure 3 Evolution of the sewage PSD in seawater during flocculation for the sewage sample collected from Stanley STW: (a) experimental observation and (b) numerical simulation

the average settling velocity of the particles increased from 3.2 to 7.2 m/d after 35 min of flocculation. The increase in the average settling velocity was less significant in the following 10 min. Numerical simulations could reproduce the similar increase in the settling velocity of sewage particles with the flocculation time. The average settling velocity increased from 1.8 to 5.2 m/d for the SCI sewage particles and from 2.9 to 9.1 m/d for the Stanley sewage particles after 45 min of flocculation. The simulation results were in good agreement with the experimental measurement. It was demonstrated that flocculation transformed small sewage particles into lager aggregates, increasing the sedimentation flux of sewage solid matters in seawater.

Coagulation and sedimentation of sewage particulates after marine outfall discharge

Both the laboratory experiments and numerical simulations indicate the importance of coagulation in the transport and sedimentation of the solid pollutants from sewage discharge in marine waters. The role of particle flocculation is particularly vital in the early phase of outfall discharge, i.e., initial releasing and intermediate transport. Within a short period after sewage discharge, the dilution factor is low and particles remain at a high concentration level. Coagulation can take place at a fast rate, transforming small sewage particles into large aggregates. In the later phase of sewage outfall discharge, particles are greatly diluted by seawater. However, coagulation still can lead to a continuous PSD evolution within a longer duration time. The growth in particle size brought about by

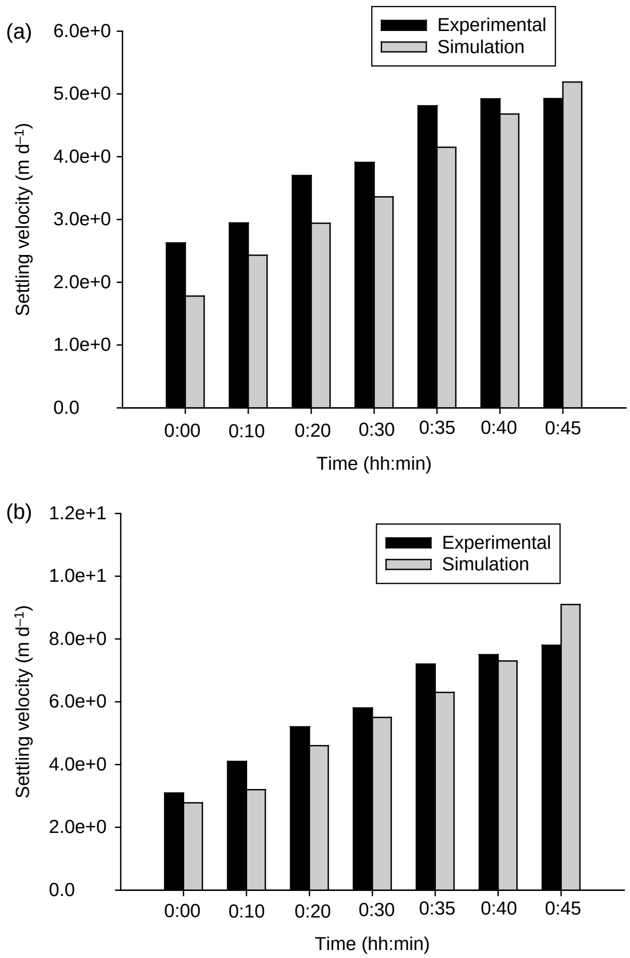

Figure 4 Change of the average settling velocity of sewage particles with the flocculation time for the sewage sample from: (a) the SCI STW and (b) the Stanley STW

coagulation results in a considerable increase in the settling rate of the sewage particles. As a result, more solid pollutants would settle and accumulate on the seabed near the outfall site rather than being transported by the current from the discharge region.

In addition, the experimental result also suggests the fractal nature of the sewage particle aggregates formed by flocculation. Fractal aggregates have a loosely packed structure, whose density decreases as the size increases. In this laboratory study, particle sizes increased continuously during the flocculation process. However, the average particle settling velocity did not show substantial increase in the later phase of the flocculation test. It is apparent that, although particles became larger with flocculation, the density of these fractal aggregates actually decreased. The increase in particle size might have been offset by the decrease in particle density, eventually resulting in a minimum change in settling velocity.

Conclusions

Laboratory experiments using a flocculator-imaging system demonstrated a significant evolution in the size distribution of sewage particles in seawater after marine outfall discharge. Flocculation transformed small particles to larger, fast-settling particle aggregates. As a result, the average settling velocity of the sewage particulates increased more than twice. A mathematical model that includes the new fractal-curvilinear particle flocculation kinetics also was developed for the transport dynamics of solid pollutants in marine waters. The numerical simulations were in good agreement with the results of laboratory experiments. Both the experiments and simulations suggest the important role of coagulation in the transport and sedimentation of sewage particles in marine waters, especially in the early phase of outfall discharge. Hence, solid pollutants in the wastewater discharge would deposit more closely in the vicinity of the outfall site. These research findings will improve our understanding of the coagulating and transferring behavior of sewage particulate matter in seawater and further increase our ability to predict the fate and transport of sewage pollutants in marine waters.

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