Variation in the Settling Behavior of Particulate Suspension in Saturated Gravel Layers

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ABSTRACT

The gravitational settling of solid particles in saturated porous media, which is common in various engineering processes and natural phenomena, was investigated experimentally. This study examines the settling pattern of fine particles suspended in saturated porous media composed of gravel layers. The experiments were conducted by varying the physical properties of particles and fluid, particle concentration and the pore scale of porous media. The three-dimensional settling behaviors of suspend particles in an invisible porous media were observed by using refractive index matching together with sheet laser scanning techniques. The experimental results showed that various settling patterns were shown depending on the particle size and concentration. Under conditions of large particle size with a small concentration, suspended particles settle individually through gaps between gravels in the direction of gravity with the velocity similar to that of an isolated particle. However, small particles with large concentrations settle collectively through the pore region as if they are one continuous fluid. In this case, the particles migrate in both vertical and lateral directions with the velocity much larger than the Stokes settling velocity. The settling velocity was quantified by image analysis of reconstructed three-dimensional images in porous media. The results indicated that the settling velocity of particles greatly depends on the settling pattern. Finally we found that the dimensionless parameter, which describes the collectivity of suspended particles in porous media, quantitatively predicts both the transition of settling pattern and the settling velocity.

Keywords: particulate suspension, porous media, gravel layer, settling pattern

Introduction

The migration of fine particles in saturated porous media is a fundamental phenomenon in various engineering processes or natural phenomena, relating to geophysics, environmental engineering and colloidal science. A lot of experimental and numerical studies have been conducted in various engineering and science fields [1-4]. Most of these studies have treated the particle migration in the porous media as advection-dispersion processes with adsorption and desorption on the media surface and have examined the macroscopic transport of suspended particles, i.e., the spatiotemporal variation in local concentration of suspended materials.

However, the migration process at particle-size scale, i.e., how individual particles migrate through the pore region in liquid-filled porous media, has not been fully understood. It becomes more complicated when the gravity effect is significant. For example, even in the sedimentation process in a simple container, the particles exhibit complex behaviors, such as the complicated concentration dependence of the hindered settling velocity [5,6], the occurrence of velocity fluctuations at large scales [7,8], and so on. In addition, particles suspended in liquid sometimes behave collectively to form density-induced convection [9-13]. Particularly in systems where the concentration gradient of particles exists in the opposite direction of gravity, the gravity-induced instability (Rayleigh-Taylor instability) results in a large-scale collective motion and enhances the settling velocity by hundreds of times [11].

The settling behavior of particles suspended in saturated porous media would be more complicated depending on the size and the space-filling properties of pores. The purpose of this study is to clarify the dependence of the migration of suspended particles in the gravity direction in saturated porous media on the physical properties of particles and fluid, suspended conditions, and pore lengthscales. As a demonstration, Figure 1 shows the settling behavior of fine particles in water-saturated gravel layers observed in a simple experiment. The gravel with a diameter of 5-10mm was filled in a 20 mm×400 mm×400 mm acrylic rectangular vessel and was saturated with water. The suspension which consists of wheat flour and water was then poured carefully above the saturated gravel layer to avoid disturbance. The gravitational settling behavior of the suspension through the pore region in the gravel layer was observed by changing the volumetric concentration of the flour particles.

In case of a small concentration (ϕ = 0.05) shown in Fig. 1 (a), the flour particles settle in the pore space almost evenly and partially deposit on the gravel. Whereas at a moderate concentration (ϕ = 0.1) in Fig. 1 (b), particles settle almost vertically forming several streaks in selected pore regions. In the case of a large concentration (ϕ = 0.20) shown in Fig.1 (c), the particles invade into manyselected pore networks and migrate laterally. The settling velocity was greatly enhanced with increasing the concentration.

Obviously, the settling of particles at large concentrations is considered as collective settling, i.e., the suspended particles behave like a continuous fluid [11]. The above demonstration indicates that

(a) ϕ = 0.05 (t =75s) (b) ϕ = 0.10 (t =65s) (c) ϕ = 0.20 (t =35s)

Fig.1 Settling behavior of wheat flour-water suspensions in gravel layer (ϕ: particle volumetric concentration, t : settling time).

the gravitational settling of fine particles in saturated porous media shows various settling patterns complicatedly depending on the suspended conditions. This study aims to understand the collective settling behavior of fine particles in saturated porous media fundamentally. The dependency of the settling pattern and the settling velocity on the suspended conditions of particles and pore scales in the media was investigated experimentally. The settling pattern in the pore was classified and the settling velocity at each pattern was quantitatively examined using a special measurement system that allows us to visualize the particle behaviors inside of porous media. From the experimental results, the collectivity of particulate suspension was redefined using the pore lengthscales and the transition of settling pattern was described by a new dimensionless parameter.

Experimental Method

Experimental apparatus and laser scanning method

In the experiment, both laser scanning and refractive index (RI) matching methods were used to observe the inside of invisible 3D porous media. Figure 2 shows a schematic of the experimental system. The experimental vessel is an acrylic rectangular container with thickness D = 25 mm and height H = 60 mm and width W = 50 mm. The vessel was filled with transparent glass spheres of the same diameter randomly and the pore region was filled with liquid, which was modeled saturated gravel layers.

The cross-section of porous media (gravel layer) was visualized by a laser scanning technique. A sheet laser source (Japan Laser, DPGL-1W), a USB camera (FLIR, FL3-U3-13Y3) with a variable focal length lens (Edmund Optics, Varifocal Lens 9-90mm) and a mirror were mounted on a metal frame fixed on a linear translation stage (Oriental motor, DRSM42RG) controlled by a personal computer. The maximum speed of the stage was 50 mm/s and the minimum translation distance was 0.001 mm.

The mirror changed the direction of the laser sheet light and irradiated it vertically inside the vessel to project the internal cross-section of porous media. The translational stage moves the metal frame horizontally at a constant speed and stops it at arbitrary positions. The USB camera took cross-sectional images of porous media from the side. The settling velocity of suspension was much smaller

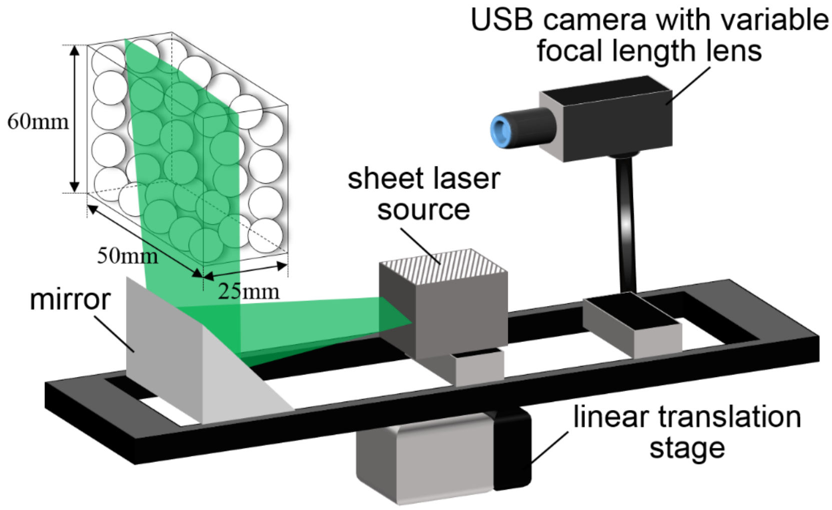


Fig.2 Schematic diagram of the experimental system.

than the translation speed of the stage. We obtained the 3D behavior of suspended particles inside the porous media by reconstructing the cross-sectional images at each instant of time.

Refractive index matching

To visualize the inside of porous media, the refractive index matching method were used. The refractive indices (RI) of the liquid in the pore was matched with that of glass spheres that make porous media. The RI of pore liquid was controlled by mixing three types of silicone oils and was adjusted to have the same as that of the glass spheres (n =1.52) used in this study. The methylphenyl silicone oil (Shin-Etsu Silicone, Kf-54) with moderate viscosity (μ_f=0.43 Pa·s) and low RI (n =1.51),

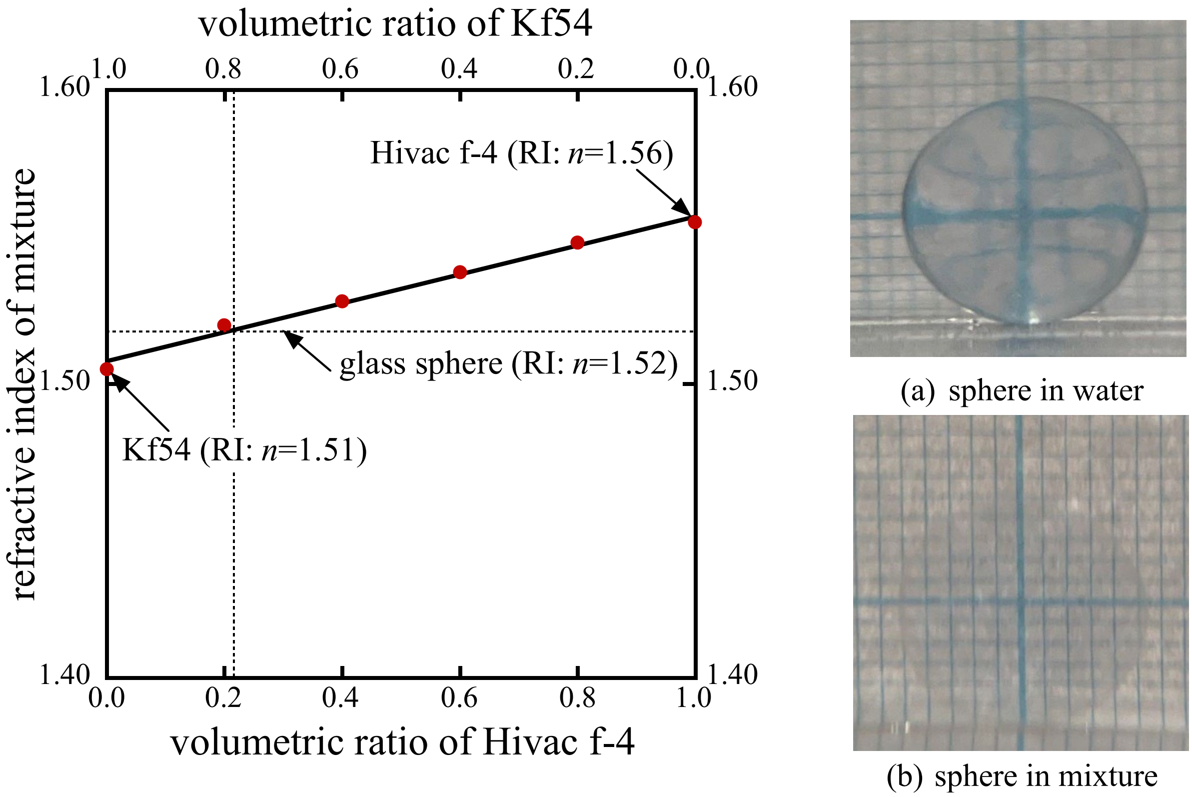


Fig.3 Refractive index of mixture of different-typed silicone oils.

and that (Shin-Etsu Silicone, Hivac f-4) with low viscosity (μ_f=0.039 Pa·s) and high RI (*n* =1.56) were mixed. Figure 3 shows the measured results of the RI of mixture of the two silicone oils. The RI of a mixture changes almost linearly with changing the volumetric ratio of each oil. As shown in the figure, mixing two oils in the ratio of 0.22 (Hivac f-4) : 0.78 (Kf-54) causes the RI to be the sameas that of the glass spheres. Fig.3 also indicates the images of a glass sphere in water (*n* =1.33) and that in the mixed silicone oil (*n* =1.52). The grid behind the glass sphere become distorted when the RI of the liquid does not match with the sphere (Fig.3a). In contrast, the grid remains undistorted behind the sphere in the mixed silicone oil (Fig.3b). Therefore the behavior of particulate suspension inside the glass spheres can be observed if the bed is filled with silicone oil of the same RI. In the experiment, the viscosity was adjusted by adding a small amount of the third type of silicone oil (Shin-Etsu Silicone, KF-54 hv). The viscosity of the liquid mixture was measured by a viscometer (Brookfield, DV2T) at each experiment. The experiment was performed under room temperature condition. The effect of temperature change on fluid properties under these conditions was confirmed to be negligible.

Experimental conditions and procedures

This study conducted fifteen experiments to examine the settling behavior of particulate suspension in gravel layers. Table 1 shows the physical properties and concentrations of the suspensions used in this study. The suspension were made of fine glass particles and the same liquid as that filled in the porous media. The diameter of suspended particles is d_p = 30, 60, 100, 207 and 454 μm. The density of particles is ρ_p = 2300, 2544 and 2590 kg/m^3. The concentration of suspension is ϕ = 0.001, 0.01

and 0.02. The viscosity of the silicone oil mixture used as the liquid of the particle suspension was adjusted to a constant value (μ_f=0.213 Pa·s), except for condition IX (μ_f=0.630 Pa·s). The liquid density is ρ_f= 1074 kg/m^3 in all cases. In order to examine the pore scale dependence of suspension

Table 1 Experimental conditions

	d_p [μm]	ρ_p [kg/m^3]	ϕ [–]	μ_f [Pa·s]	U_{St} [mm/s]	$(L_p/d_p)\phi^{1/3}$ [–]	$(L_p/d_p)\phi^{1/2}$ [–]
(a) L_p = 10mm							
I	30	2300	0.01	0.213	0.00282	71.8	33.3
II	60	2300	0.02	0.213	0.0113	45.2	23.6
III	60	2300	0.01	0.213	0.0113	35.9	16.7
IV	60	2300	0.001	0.213	0.0113	16.7	5.3
V	100	2300	0.01	0.213	0.0313	21.5	10.0
VI	100	2300	0.001	0.213	0.0313	10.0	3.2
VII	207	2544	0.01	0.213	0.161	10.4	4.8
VIII	207	2544	0.001	0.213	0.161	4.8	1.5
IX	454	2590	0.01	0.630	0.270	4.7	2.2
(b) L_p = 8mm							
X	30	2300	0.01	0.213	0.00282	57.5	26.7
XI	60	2300	0.01	0.213	0.0113	28.7	13.3
XII	100	2300	0.01	0.213	0.0313	17.2	8.0
(c) L_p = 6mm							
XIII	30	2300	0.01	0.213	0.00282	43.1	20.0
XIV	60	2300	0.01	0.213	0.0113	21.5	10.0
XV	207	2544	0.01	0.213	0.161	6.2	2.9

behavior, the diameter of the glass sphere which modeled gravels was changed as L_p = 6, 8 and 10 mm. The porosity of the spherical bed is approximately 0.4 to 0.6 near the center of the experimental vessel. Table 1 also shows the Stokes settling velocity for each condition, which is defined as follows.

$$U_{St} = \frac{(\boldsymbol{\rho}_p - \boldsymbol{\rho}_f)\, d_p^2 g}{18\boldsymbol{\mu}_f} \tag{1}$$

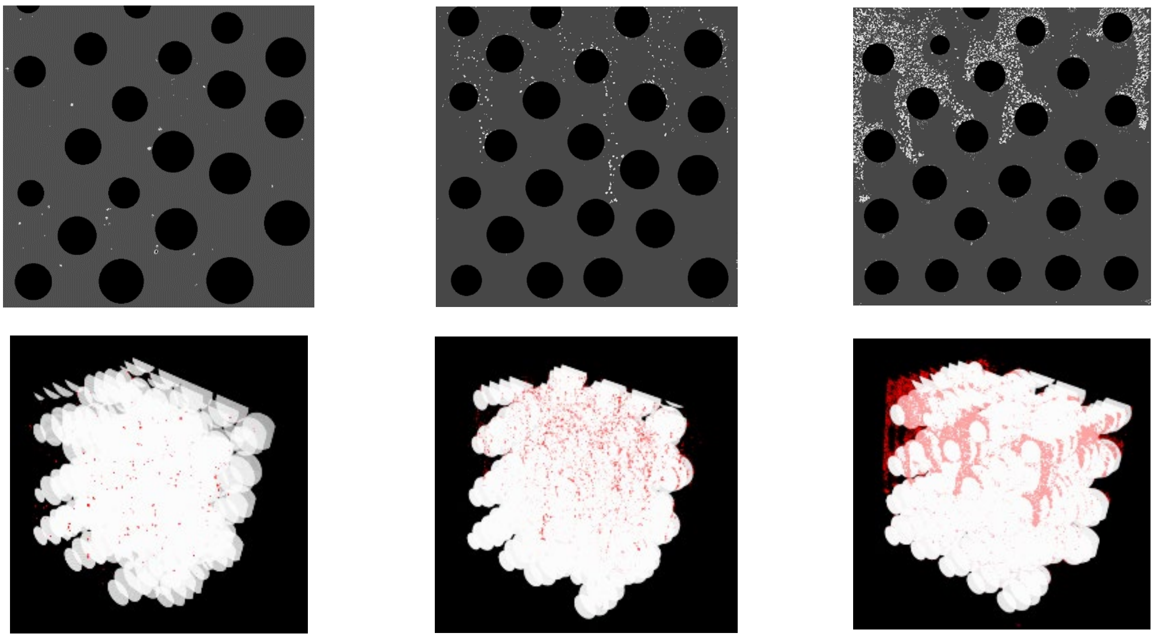
The experimental procedures are as follows. To make modeled porous media, the glass spheres were packed randomly in an experimental vessel and the mixed silicone oil was filled in the pore region. The suspension was made of fine particles with the same liquid that filled the porous media, and poured into the reservoir tank, which is put above the experimental vessel via a thin stainless partition. Then the partition was removed and the settling behaviors of suspension in the pore region of the porous media was observed. The linear stage was operated at a constant time interval and the cross-sectional images were taken using the USB camera system. In this study, 11 cross-sections at 2 mm depth were selected for observation and image processing.

Results and discussion

Settling behavior of suspended particles in porous media

Figure 4 shows the cross-sectional and 3D reconstruction images of the settling behavior of the suspension under various particle size and concentration conditions (conditions III, VII and VIII). The 3D images were made by superimposing all 11 cross-sectional images for respective conditions. In the cross-sectional images, the black regions indicate glass spheres that make porous media and gray regions indicate pores, whereas the white dots indicate suspended particles. It should be noted that each white dot does not necessarily indicate individual particles. In particular, the cloud of white dots represents the suspension existing region under the condition of small particle size and large concentration, as shown in Fig.4 (c). In the 3D reconstruction images, the translucent white area shows the porous media (glass spheres) and the cloud of red dots indicates the suspension.

The experimental results in Fig.4 (a) (condition VIII) show that the suspended particles with large particle size and low concentration settle almost vertically. Each particle moves individually interrupted by the presence of glass spheres. In contrast, the settling behavior at small particle size and high concentration (Fig.4c, condition III) is quite different from the large-size particle settling, i.e., the particles settle in clusters through specific pores. In this case, the suspension behaves like a continuous fluid and moves laterally as if the other fluid invades into saturated porous media. Fig.4 (b) shows the settling behavior of large particles with large concentrations (condition VII), which corresponds to intermediate conditions between conditions III and VIII. In this case, the particles settle almost vertically, but they move selectively in the pores with a high variance in vertical settling



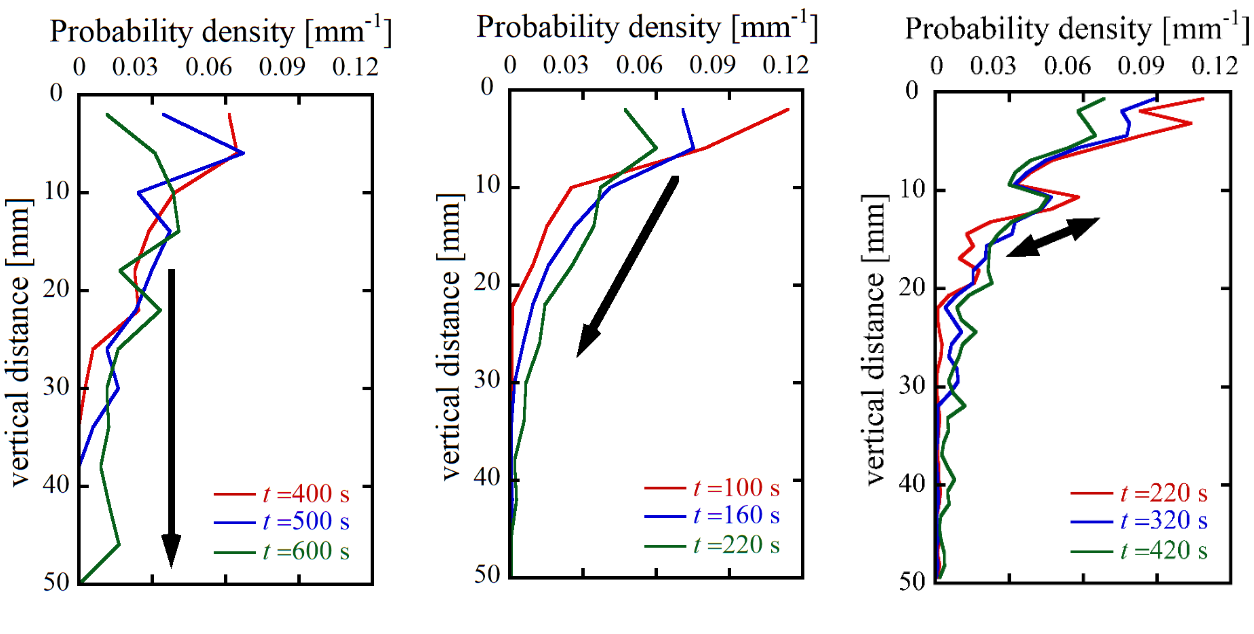
(a) condition VIII (d_p=207μm, ϕ=0.001) (b) condition VII (d_p=207μm, ϕ=0.01) (c) condition III (d_p=60μm, ϕ=0.01)

Fig.4 Settling behaviors of suspended particles in porous media for L_p=10mm (upper: 2D images at arbitrary cross-section, lower: 3D reconstruction images from 11 cross-section). The particle size is the same for conditions VII and VIII, while the concentration is the same for conditions III and VII. The settling time is (a) t =600 s, (b) t = 220 s and (c) t = 420 s, respectively.

velocity. As shown in the above results, the particle size and suspension concentration significantly affect the settling behavior of suspension, even in porous media.

Classification of settling pattern

For a more quantitative classification of settling patterns, the temporal change in the particle-existing regions in porous media was examined. Figure 5 shows the probability density of the particle-existing region at each vertical position, corresponding to the conditions shown in Fig.4. The probability density was calculated from the volume of pores in which suspended particles existed at respective vertical position. Fig.5 (a) indicates that, in the case of large particle size and small concentration which is shown in Fig.4 (a), the probability density of the particle existing region is almost constant at each height and extends downward with time, which indicates that the particles settle vertically while dispersing with nearly a constant velocity. On the other hand, the probability density in the intermediate condition shown in Fig.5 (b) monotonically decreases in the vertical direction. This indicates that the suspension moves downward in specific pores with various velocities



(a) condition VIII (d_p=207μm, ϕ=0.001)

(b) condition VII (d_p=207μm, ϕ=0.01)

(c) condition III (d_p=60μm, ϕ=0.01)

Fig.5 Probability density of particle-existing region for L_p=10mm.

as shown in Fig.4 (b). The probability density of small particles with high concentration (Fig.5c) has an uneven profile. This means that the particles move horizontally at a certain height, which is shown in Fig.4 (c).

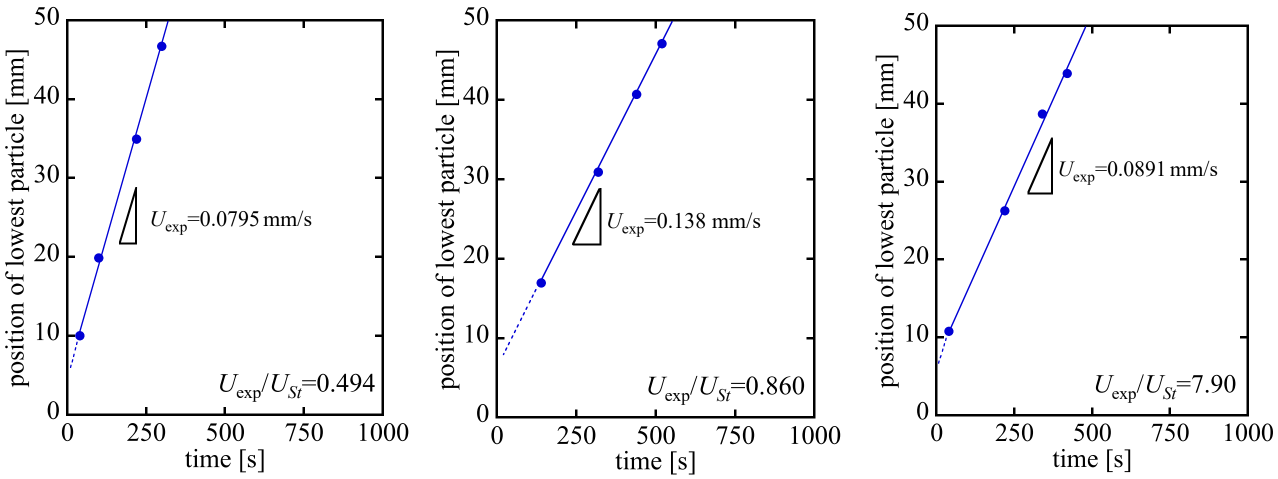
From the probability density of the particle-existing region shown in Fig.5, the settling pattern of suspended particles in saturated porous media can be classified and named from their space-filling properties as follows; 1) the particles behave individually and they settle vertically while dispersing with nearly constant velocity (one-dimensional settling), 2) the particles settle almost vertically in specific pores with various settling velocities (two-dimensional settling), and 3) the suspended particles behave collectively like a continuous fluid and invade into pores in vertical and lateral directions (three-dimensional settling).

Actually, the settling patterns of particles transit continuously as shown in previous study [11]. Even when using the probability density function of vertical position to show the difference in order to make the classification quantitatively, it cannot be clearly distinguished in some cases. Therefore it should be noted that it is undeniable that there is subjectivity in the settling patterns shown here under some conditions.

Settling velocity of particles

The variance of the settling pattern in saturated porous media bring about the variance of the settling velocity. Figure 6 shows the temporal change in the vertical position of the lowest particles under the conditions III, VII and VIII. The settling velocity was calculated from the slope of the lines in Fig.6.

In all cases, the particles gave nearly constant velocity except for the beginning stage. In particular, the velocity in three dimensional settling as shown in Fig.6 (c) increases exponentially at the beginning and reaches a constant value. This exponential increase is due to the gravity-induced instability at the concentration interface [9-13]. The settling velocity at the later stage normalized by the Stokes settling velocity at each condition is described in Fig.6 and U_{exp}/U_{St}=7.90 (condition III), 0.860 (condition VII) and 0.494 (condition VIII), respectively. That is, the normalized velocity is larger in the order of three-, two- and one-dimensional settlings. These results indicate that the collective settling of suspended particles much enhances the settling velocity.



(a) condition VIII (b) condition VII (c) condition III

Fig.6 Temporal change of position of the lowest particles for conditions III, VII and VIII.

Figure 7 shows the settling velocity of suspended particles obtained from all experiments for L_p=10 mm, with the settling patterns classified from the probability density. Where experimental results are not shown, the boundary expected by extrapolation are given. The horizontal axis shows the particle diameter and the vertical axis shows the settling velocity normalized by the Stokes settling velocity U_{exp}/U_{St}. As shown in the figure, the normalized settling velocity of smaller particles indicates larger values, i.e., the settling velocity of small particle is much larger than the Stokes velocity. Fig.7 also shows that the settling velocity increases with increasing the concentration.

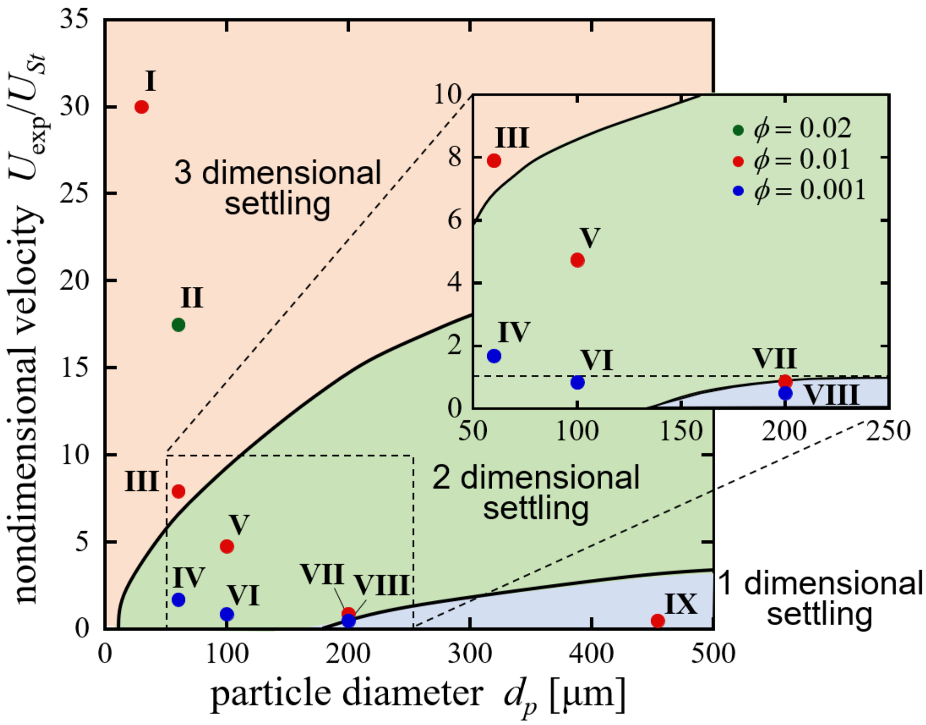


Fig.7 Settling velocity and settling pattern of particles in porous media for L_p=10mm.

Therefore the normalized settling velocity $U_{\exp}/U_{St}$ is a decreasing function of the particle size d_p and an increasing function of the concentration ϕ.

The variance of the settling velocity is obviously caused by the transition of the settling pattern. When the particle size is large and the concentration is small (e.g., conditions VIII, IX), the settling pattern is classified as one-dimensional settling, in which the particles settles almost vertically in the pore regions while being obstructed by gravels (glass spheres). In this case, the particle velocity is the same as or slightly less than the Stokes settling velocity.

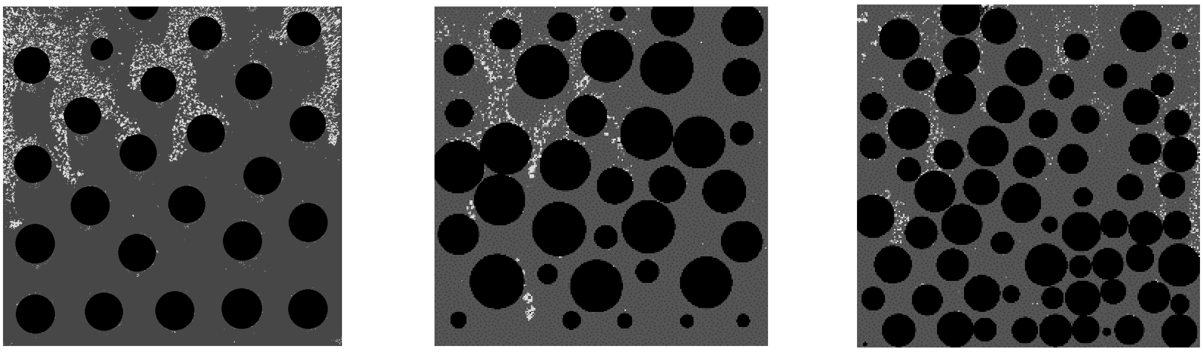
On the other hand, the particle size is small and the concentration is large, the settling pattern transitions to two-dimensional or three dimensional settlings and the particle velocity is dozens of times greater than the Stokes velocity. This is obviously due to the collective motion of suspended particles. If the suspended particles are far from each other, they settles independently with little influence from the hydrodynamic interaction. The inter-particle distance l is obviously a function of the particle diameter d_p and the concentration ϕ, and is roughly estimated as $l \sim d_p/\phi^{1/3}$. Therefore the inter-particle distance in suspensions with small particle size and large concentration becomes small. In such cases, the suspended particles behave collectively as one continuous fluid immiscible to a lower liquid [11]. In consequence, the volume exchange to the lower liquid produces a large-scaled convection in the pore region and the settling velocity is much larger than that of the isolated particle. This immiscible nature of the suspension interface results from swarms of Stokeslet, i.e., the flow created by each particle prevents the surrounding fluid from penetrating the suspension [16,17]. These results indicate that the settling velocity of particles drastically changes with the settling pattern.

As described in the previous study [11], the nondimensional parameter decides the miscibility or immiscibility of the concentration interface of suspension. The parameter is called "collectivity" defined as $C = (L/d_p)\,\phi^{1/3}$ (L: channel width) for the settling of a rectangular channel. Concerning the flow pattern, the suspended particles in behave as a continuum for $C > 33$, while they behave individually for $C < 5$. The suspended particles shows both individual and collective behaviors for $5 < C < 33$ [11].

Obviously, the transition of flow pattern shown in Fig.7 is due to the collectivity change of suspensions. Table 1 also shows the collectivity of each condition, which is defined using the diameter of glass sphere L_p as the representative lenghscale of pores, instead of the channel width. In general, the actual pore size in porous media composed of spheres is somewhat less than the sphere diameter [18]. Nevertheless, the collectivity shown in Table 1 well represents the transition of flow pattern as shown in Fig.7.

Pore-scale dependence

The dependency of the settling pattern of suspension on the pore size in porous media was also examined. Figure 8 shows cross-sectional images of the settling of suspension in porous media composed of glass spheres with diameters of L_p = 6, 8 and 10 mm. The diameter of suspended particles is 60 μm and the volumetric concentration is ϕ = 0.01 in all cases (conditions of III, XI and XIV). As shown in Fig.8 (a), the suspended particles behave as a continuous fluid and move both vertically and horizontally in large-size pores (L_p =10 mm), while the particles move almost vertically in small-size pores (L_p = 6 mm), which is shown in Fig.8 (c). This indicates the flow pattern transitions from three-dimensional to two dimensional settlings due to the decrease in the



(a) condition III (b) condition XI (c) condition XIV

(L_p=10mm, d_p=60μm, ϕ=0.01) (L_p=8mm, d_p=60μm, ϕ=0.01) (L_p=6mm, d_p=60μm, ϕ=0.01)

Fig.8 Cross-sectional images of settling behaviors of suspended particles in porous media. The settling time is (a) t = 420 s, (b) t = 440 s and (c) t = 660 s, respectively.

pore size. As shown in Table1, the decrease in pore size bring about the reduction in the collectivity and consequently the transition of the flow pattern.

Here we provide a unified interpretation of the effects of the particle size, the concentration, and the pore scale on the settling velocity of suspension in porous media. An assembly of particles settling as a single blob is considered. As described in the previous studies [14,15], the settling velocity of the suspension blob with a size of L_p can be expressed from the analogy of Stokes settling velocity as follows.

$$U = K\frac{(\rho_s - \rho_f)\, g L_p^{\,2}}{\mu_f} \tag{2}$$

where ρ_s is the apparent density of suspension and K is a constant depending on the shape of the blob.

The apparent density of the upper suspension is then expressed as follows.

$$\rho_s = \phi \rho_p + (1 - \phi) \rho_f \tag{3}$$

Substituting Eq.(3) into Eq.(2), the settling velocity can be expressed as follows.

$$U = K \frac{\phi(\rho_p - \rho_f)\, g L_p^{\,2}}{\mu_f} \tag{4}$$

The right-hand side of Eq. (4) can be expressed in terms of the Stokes settling velocity U_{St}, which is the settling velocity of an isolated particle described in Eq. (1), as follows.

$$U = K \left(\frac{L_p}{d_p} \phi^{\frac{1}{2}} \right)^2 U_{St} \tag{5}$$

Eq.(5) shows that the collective settling velocity of the suspension is proportional to the square of $(L_p/d_p)\,\phi^{1/2}$, which is defined as the modified collectivity C_{mod} in the previous study [15]. As reported in our precious studies, the collectivity C describes the flow pattern of suspended particles [11], whereas C_{mod} is related to the settling velocity of suspension [15], although they are very similar.

Figure 9 shows the settling velocity of particles normalized by the Stokes settling velocity U_{St} obtained from all experiments in this study with the nondimensional number C_{mod} described in Eq.(5), as well as the settling pattern for respective conditions. Because the definitions of C and C_{mod} are almost identical except for the gentle function $\phi^{1/6}$, the horizontal axis of Fig.9 can almost describe the transition of flow pattern. In the case of one-dimensional settling, the settling velocity is almost identical or a little bit smaller than the Stokes settling velocity because of the interruption by the glass spheres forming the porous media. On the other hand, the settling velocity increases as the flow pattern transitions to two- or three-dimensional settling. In the three-dimensional settling, the velocity

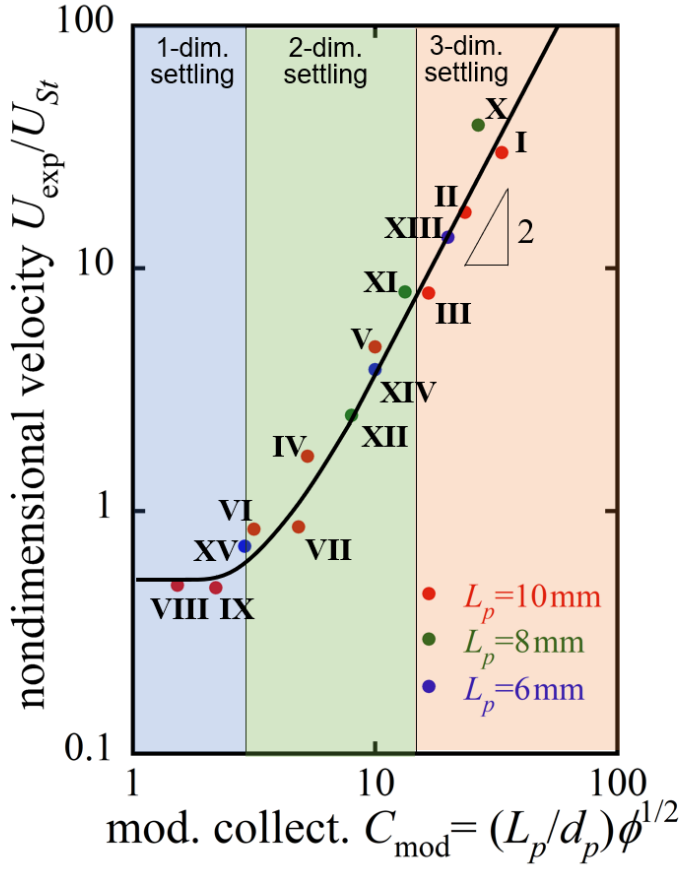


Fig.9 Transition of settling pattern and settling velocity in gravel layers of various sizes.

is proportional to the square of the modified collectivity $C_{\mathrm{mod}} = (L_p/d_p)\,\phi^{1/2}$, as expected in Eq.(5). Although the classification the settling pattern shown here is not rigid, C_{mod} is likely to predict both the settling pattern and the settling velocity of suspended particles even in porous media.

The above results show that the settling behavior of suspended particles is affected by pore sizes in porous media, in addition to the physical properties of particle and fluid and the concentration. For example, even if the same suspension settles in porous media, changes in pore size can alter the settling pattern and, consequently, the settling velocity can change dramatically. Therefore, in order to predict the settling behavior of particles in porous media quantitatively, it is essential to understand the influence of the collective nature of the suspension, as shown in Fig.9.

Conclusions

Experiments were conducted to investigate the settling behavior of fine particles in saturated porous media composed of spherical glass particles, which models gravel layers. The settling behavior of suspend particles in invisible porous media was observed by utilizing sheet laser scanning and RI matching techniques. The experimental results showed that the settling behavior of the particles was significantly influenced by the particle size and suspension concentration. We classified the settling behavior in porous media into three patterns based on their space-filling properties; one-dimensional settling in which the particles settle individually and vertically with almost constant velocity, two-dimensional settling in which the particles settle almost vertically in specific pores with the velocity variances, and three-dimensional settling in which the particles settle collectively like a continuous fluid and invade several pores. The settling velocity greatly depends on the above-defined settling patterns. In the case of one-dimensional settling, the particle velocity was close to the Stokes settling velocity, whereas the velocity in three-dimensional settling was several tens of times faster than the Stokes settling velocity.

We also performed experiments by changing the size of the gravel consisting of porous media to examine the effect of pore size. The results show that the settling pattern of the suspended particles changes in a complex manner depending on the pore size. The transition of settling pattern and the resultant change of settling velocity can be explained the dimensionless number describing the collectivity of suspended particles, which was defined in the previous study. The dimensionless number defined by the representative pore size (gravel size) in porous media $C_{\mathrm{mod}}=(L_p/d_p)\phi^{1/2}$ well predicts both the transition of the settling pattern and the settling velocity quantitatively. For example, the velocity in a three-dimensional settling is scaled by the square of C_{mod}.

The above results show that the settling velocity of particles in porous media changes drastically depending on the various conditions. Therefore, if the gravitational settling of particles in saturated porous media is considered as assemblies of isolated particles with their Stokes velocity, there will be a significant deviation from the actual behavior. Therefore, it is important to understand the collective motion of settling particles in porous media precisely.

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Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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