Effect of the concentration of NaCl and cylinder height on the sedimentation of flocculated suspension of Na-montmorillonite in the semi-dilute regime

Muhamad Ezral Bin Ghazali[1] · Yanuar Argo[2] · Harumichi Kyotoh[3] · Yasuhisa Adachi[1] [1] A4

[1]Graduate School of Life and Environmental Sciences, University of Tsukuba, 1-1-1 Tennoudai, Tsukuba, Ibaraki 305-8572, Japan

[2]Assessment Institute of Agricultural Technology, Jln. Kayuambon No. 80, Lembang, Bandung Barat, Jawa Barat, Indonesia

[3]Institute of Engineering Mechanics and Systems, University of Tsukuba, 1-1-1 Tennoudai, Tsukuba, Ibaraki 305-8573, Japan

Abstract

In this study, we focused on the effect of the degree of floc growth on the moving velocity of the interface between sediment of flocculated montmorillonite and supernatant in the semi-dilute suspension, which is characterized by the start of an extremely slow movement of interface followed by an abrupt settling and ending in consolidation. Na-montmorillonite suspension coagulated under different ionic strengths, ranging from 0.5 M to 1.5 M of NaCl, was placed in a settling cylinder. The initial height of suspension was varied from 13 cm to 50 cm. The flocculated suspension was left to settle in the cylinder after the manual mixing of end-over-end. Changes in the height of the interface between the flocculated sediment and the transparent supernatant were measured as a function of elapsed time. It was confirmed that the maximum settling velocity increased with an increase in the height of cylinder within the range of our measurement. This tendency was found to be more significantly pronounced by the growth of flocs. This result indicates the presence of a feed-forward mechanism to enhance the upward motion of fluid or downward motion of flocculated sediment, or both. That means, sedimentation is accelerated by the growth of big flocs, and the growth of big flocs is accelerated by the sedimentation. These motions will eventually induce the generation of an upward plume or channel of water. The formed plume flutters slowly with rather a large scale. We term this phenomenon the "sedimentation turbulence."

Na-montmorillonite, Sedimentation, Semi-dilute suspension, Cylinder height. Sedimentation turbulence

Introduction

Colloidal substances, soil, and suspended solids in water are ubiquitous in an aquatic environment. These substances can often be found in a flocculated state. Despite its ubiquitous presence and importance to transportation in the aquatic environment, relatively little attention has been paid to the sedimentation behavior of flocculated suspension. In paddy farming, this phenomenon can be commonly found in the processes of puddling (Adachi 2019). Previous works have reported the discharge of high-turbidity water into river water during or after puddling (Wakai et al. 2005; Sudo et al. 2009). Fine sediment discharged from the paddy surface by excess water moving into the river causes an increase of water turbidity in the downstream basin. Meanwhile, in the process of irrigation, cohesive sediment tends to accumulate tentatively in the still-water part of irrigation and drainage channels. But such tentative sediment can be easily flushed out by the change of flow rate in the canal. In the puddling season, the river water will be polluted with chemical substances originating from fertilizers and other agrochemicals, which are sorbed to the surface of clay particles composing the flocculated sediment. Such contaminants can potentially endanger the entire ecosystem (Winterwerp and Kestern 2004). In the natural aquatic environment, the majority of fine particles are present in a flocculated form. Therefore, flocs can be regarded as a very important unit of transportation as compared to individual particles, and flocculated material will influence a wide array of environmental phenomena. The sedimentation process of flocculated materials under gravity can be regarded as the most fundamental issue that is yet to be clarified in the transportation process of chemical substances via water.

Sedimentation behavior

A framework of the theory of sedimentation was worked out by Kynch (1952). The theory has been considered assuming mainly non-colloidal materials (Davis and Acrivos 1985). Imai (1981) classified the sedimentation behavior of coastal sediment, which has the natural tendency to flocculate, into three different regimes as a function of the suspension concentration. They are, dilute, semi-dilute, and concentrated regimes. In the dilute regime, the formed flocs settle freely. Since larger flocs settle faster and smaller flocs settles slower, smaller flocs are apt to remain in the upper space. With such situation, the boundary between the sediment and the supernatant becomes unclear. By contrast, in the semi-dilute regime, mutual interactions among the flocs will form network-like structure and the settling process effectively induce an idle time before the flocs start to settle. The difference between the dilute and the semi-dilute regime is the appearance of a clear boundary between the sediment zone and supernatant zone. This is probably because all the smaller flocs will be captured by the network-like structure formed by other bigger flocs. That is, the network-like structure essentially acts as the filter of all small flocs. This means that in the semi-dilute regime, flocs in the sediment appear to interact to form a phase of sedimentation that has a clear interface with the transparent and supernatant zone. In the concentrated regime, an initially formed network structure of flocculated sediment settles very slowly under its own weight. In the present study, we focused on the second regime.

The progress of sedimentation in a semi-dilute regime can be further characterized into three stages. They are, starting with an initial flocculation stage, followed by a rapid sedimentation stage, and ended by a very slow consolidation stage. Michaels and Bolger (1962) presented an analytical method of hindering sedimentation of flocculated kaolinite using the result of fluidized bed reported by Richardson and Zaki (1954) in which we need to assume some representative size of flocs. Although their data of the experiment showed a tendency for the maximum rate to affected by the height of the suspension, they did not mention anything on this phenomenon. To understand the sedimentation process of flocculated suspension, our insight in the present study is that it is necessary to pay attention to the factor of floc growth during sedimentation.

In the present study, we have chosen a system of the coagulated suspension of Na-montmorillonite, with which extremely big flocs can be formed simply by the increase of the concentration of NaCl (Adachi et al. 2019). This characteristic has been regarded as an ideal one for studying the physical properties of flocculated suspension (Wu and Adachi 2016; Miyahara et al. 2002; Kobayashi and Adachi 2008). Moreover, montmorillonite can be regarded as an important clay mineral for industrial, agricultural, and environmental processes, and many aspects of this clay remain to be studied (Uddin 2008). In our previous study, we highlighted the relationship between microscopic heterogeneous interaction of clay particles and macroscopic behavior of Na-montmorillonite sedimentation. We have confirmed that the increase of ionic strength reduces the duration of the initial flocculation stage denoted as τ. The onset of collapse appears to be escalated by the generation of small cracks in the weakly connected sediment structure. This moment was regarded as the characteristic point corresponding to a certain degree of flocculation at which the formed gel network of flocs is collapsed by its self-weight. On the basis of this picture, we can simply conclude that τ is the time required to reach this certain degree of flocculation (Wu and Adachi 2018). The duration of the initial flocculation stage becomes smaller if the rate of flocculation is increased. This interpretation was consistent with the colloidal stability analysis of Tombácz et al. (1988), who pointed out the dominance of edge–face interaction detected as the difference in critical coagulation concentration, which appeared in a lower pH under lower ionic strength. Our result in the previous study for the difference in τ also correlated with this trend.

In the present study, we focus on the settling velocity of the second stage. We measured the location of interface between sediment and supernatant as a function of elapsed time. When the concentration of sodium chloride exceeds 0.5 M, the montmorillonite suspension is known to form big flocs irrespective of pH value (Miyahara et al. 1998). This is suitable for naked-eye observation. With this system, the behavior of maximum velocity of the second stage can be intensively analyzed by changing the height of cylinder and the concentration of NaCl.

Materials and methods

Montmorillonite suspension preparation

The following procedure was applied to prepare well-characterized samples: 1) Commercially available Kunipia-F (Kunimime Co., Ltd.) was dipped in a solution of 1.0 M NaCl to exchange unknown adsorbed cations with sodium ions. The purity of the montmorillonite content of this commercial product was confirmed by the courtesy of Agroenviromental Research Institute, using X-ray diffraction (MiniFlex, Rigaku Co., Ltd.). Based on that result, Sueto and Nakaishi (1992) reported that this commercial product is typically pure montmorillonite and confirmed the chemical composition of this clay supplied by the company (Kunimine Co., Ltd.). The purity of the same product was also reported by Nanzyo and Kanno (2018). 2) The dispersion saturated with NaCl was rinsed using the dialysis process with distilled water repeatedly. 3) The rinsing process through dialysis was conducted until the ionic concentration of the resulted supernatant reaches lower than 10^{-5} M measured by a conductivity meter (LAQUA pH/Ion/Cond. Meter F-74BW, Horiba Scientific Co., Ltd.). 4) After dialysis, the original stock suspension was prepared. The solid volume fraction of montmorillonite suspension was measured by drying out the water at 105 °C in the oven for one day. 5) The prepared dispersion of Na-montmorillonite was mixed with the NaCl solution. For the mixing procedure, the end-over-end mixing method was used; whereby the term indicates a simple mixing method of two liquids contained in two identical cylinders. In the beginning, the two cylinders were filled with the same amount of liquid of suspension (A) and the NaCl solution (B). Then, the entire liquid contained in one cylinder is poured into the other smoothly. The solution in cylinder B was poured into cylinder A within 10 seconds. Instantly, the solution in cylinder A was poured into cylinder B again within 10 seconds. The mixing procedure was repeated three times and the glass cylinders were filled with the flocculated suspension up to the required initial height.

Measurement of maximum settling velocity

The relationship between clear interface boundary and the elapsed time was established at room temperature (20 ± 1°C). The solid volume fraction of montmorillonite suspension was 2.0×10^{-4}. The NaCl concentration used in this study was adjusted to 0.5 M, 0.75 M, 1.0 M, 1.25 M, and 1.5 M. The height of settling cylinder used in this study were 13 cm, 20 cm, 25 cm, 35 cm, and 50 cm. The flocculated suspensions were left to settle in the settling cylinder after the manual mixing method of the end-over-end (Fig. 1). The experiment was conducted in triplicate and the sedimentation behavior was delineated by descriptive analysis. Changes in the height of interface between the flocculated sediment and the transparent supernatant for different levels of ionic strength were measured as a function of elapsed time.

Results

The temporal variation of the interface between the supernatant zone and the sediment zone of flocculated Na-montmorillonite are plotted in Fig. 2a-e for different concentrations of NaCl and for each different cylinder heights. As demonstrated in the figure, all plotted data demonstrate the pattern of inverse S-curve. This tendency is pronounced for the cases of higher cylinder and higher concentration of NaCl. For the case of lower concentration of NaCl (0.5 M and 0.75 M), an initial latency period was observed. This is consistent with the results reported previously (Wu and Adachi 2018). The dependency of the maximum rate of sedimentation on the height of cylinder confirmed our previous result obtained for the case of NaCl 1.0 M (Argo et al. 2016). But, here, we confirmed the tendency for a wider range of NaCl concentration.

In Fig. 3, all of the obtained maximum settling velocities are plotted against the height of cylinder. It is interesting to note that the acceleration of maximum velocity as a function of cylinder height is obviously more pronounced for the case of higher concentration of NaCl.

Discussion

Maximum velocity as a function of the cylinder height and the concentration of NaCl

According to Nakaishi et al. (2012), the difference of moving velocity during the initial stage against cylinder diameter was ascribed to the drag at cylinder wall. While in the second stage, they reported almost the same value of maximum settling velocity. That is, the value of maximum velocity is not influenced by the diameter of cylinder. Our preliminary study also confirmed that the settling velocity of aggregated Na-montmorillonite flocs in cylinders with diameters of 4.0 cm and 2.0 cm showed no clear difference (Argo et al. 2016). Therefore, we can conclude that the maximum velocity in the second stage increases with an increase of cylinder height and secondly, this increase is much more enhanced by the increase in the concentration of NaCl.

Our observation of the sediment morphology confirmed that the sediment was coarser and less homogeneous at higher salt concentration. This are notable characteristics of flocculated montmorillonite coagulated with NaCl (Miyahara et al. 1998; Wu and Adachi 2016; Adachi et al. 2019). At lower ionic strength, flocs are obviously smaller, and the appearance of the cake is much homogeneous. Miyahara et al. (1998) pointed out that Na-montmorillonite suspension is known to form big flocs in an extremely high concentration of NaCl. This ensures that visibly large montmorillonite flocs are formed to enhance the rate of sedimentation. If we can accept the reason for the enhancement of maximum settling velocity is due to the formation of bigger flocs, the reason for enhancement of the maximum settling velocity by the increment in cylinder height can be ascribed to the development of bigger flocs during sedimentation. That is, the higher the cylinder, flocs will have more chances to grow by traveling longer distances. This is the reason that the maximum velocity is enhanced by the increase in the cylinder height and by the increase of the concentration of NaCl.

Changing the concentration of NaCl will affect the macroscopic behavior, which in turn will determine the coagulation behavior. Gibbs (1983) confirmed that increasing salinity will increase the collision efficiency owing to the decrease in double-layer thickness and surface charge. Increasing salt concentration decreases the repulsive electrostatic effect, breaking weak edge–face bonds and residual strong edge–face bonds, and results in bigger flocs (Wu and Adachi 2016). However, more important reason for the development of bigger floc in the sediment is the remarkable increase of floc strength in the region of extremely high concentration of NaCl which is clarified in our recent result on the floc strength of Na-montmorillonite studied in a well-defined flow (Adachi et al. 2019). That is, if the floc strength is strong, it is more probable that big flocs formed during the sedimentation stand for the break-up.

Feed-forward mechanism enhancing sedimentation process

Based on the result of the sedimentation behavior and naked eye observation, we summarize the scenario of sedimentation of flocculated material in the cylinder as follows. Initially, during the flocculation stage, colloidal flocs are considered to grow gradually to form a loose network (Adachi et al. 2019) (Fig. 4). It is regarded as waiting time before the gel collapse (Fig. 6a-c). Consequently, as the loose cake that is formed starts to collapse, the rapid sedimentation stage sets in (Fig. 6d-e). During this stage, the bigger flocs (i.e., those formed in high salt concentration) will settle down faster than the smaller ones. Owing to the velocity difference, the collision of settling flocs will take place; this leads to the development of the flocs. In the case of higher cylinders, the distance through which flocs fall becomes longer. The falling flocs will then have more chance to collide with other small flocs and increase in size and mass, thereby accelerating their settling speed. Consequently, the rapid sedimentation commences at a different period (Imai 1981; Dobias et al. 1993). The flocs settle differently in terms of velocity, owing to their different size and density, to fill the void formed from channeling, which then creates the counter-flow that is visually observed to be similar to a small turbulent flow (Fig. 6e). It can be characterized as an unstable, irregular, seemingly random, and chaotic flow, and it certainly causes unpredictable movement of flocs (Pope 2000). We term this phenomenon the "sedimentation turbulence." This phenomenon is not well described in the previous study by Michaels and Bolger (1962) or elsewhere. The flocs motion induces turbulent flow passing through in disordered flows, which helps to rearrange the formation of the floc.The flocs formation is due to turbulent flow passing through, which increases the settling velocity as the hydrodynamic drags and adds mass affected. Consequently, the flocs collide with neighboring flocs, and they are rearranged to form bigger flocs. This feed-forward mechanism continues until the flocs hinder each other and enter the consolidation stage (Fig. 6f). The flocs settle and move further to fill the space left underneath to develop early consolidation at the bottom of the cylinder (Winterwerp and Kestern 2004; Imai 1981). It is noticeable that the sediment at the bottom of the cylinder becomes denser and more compact as the void ratio decreases over time (Fig. 5). During this final stage, the flocs settle slowly owing to their self-weight reflecting a slow sedimentation rate. To illustrate the overall progress of sedimentation as well as the sedimentation turbulence phenomenon, we have improved the schematic diagram by Wu and Adachi (2016) after a careful observation (Fig. 6).

Conclusion

The study presented here shows the effect of cylinder height on the sedimentation behavior of flocculated Na-montmorillonite in the semi-dilute regime. Our results indicate that the maximum rate of sedimentation increases steadily as a function of cylinder height. The sedimentation behavior of flocs is dependent on floc size, which in turn is controlled by salt concentration and collision rate between flocs. Our findings suggest that the size of the flocs increases owing to prolonged traveling distance in higher cylinders, coupled with the sedimentation turbulence that emerges during the gel collapse. Increasing cylinder height will allow longer traveling distance and increase the chances of aggregation of falling flocs, and thus enhance the sedimentation. The upward motion of fluid or downward motion of flocculated sediment, or both, is enhanced by the feed-forward mechanism, which creates sedimentation turbulence. Sedimentation is accelerated by the growth of big flocs, and the growth of big flocs is accelerated by the sedimentation. Additional experiments on the sedimentation behavior of Na-montmorillonite using flow visualization techniques will further elucidate this sedimentation turbulence phenomenon.

References

[1] Adachi Y (2019) Aspects of colloid and interface in the engineering science of soil and water with emphasis on the flocculation behavior of model particles. Paddy and Water Environment 17(2):203-210. https://doi.org/10.1007/s10333-019-00712-7

[2] Adachi Y, Di C, Xiao F, Kobayashi M (2019) Size, orientation, and strength of Na-montmorillonite flocs flowing in a laminar shear flow. Colloid and Polymer Science 297(7-8):979-987. https://doi.org/10.1007/s00396-019-04532-3

[3] Argo Y, Wu M, Adachi Y (2016) Effects of container height on the sedimentation behavior of flocculated suspension of Na-montmorillonite. Proceedings of the 2016 Annual Meeting of Society of Agricultural and Rural Engineering, pp 493–494, Sendai, Japan.

[4] Davis RH, Acrivos A (1985) Sedimentation of noncolloidal particles at low reynolds numbers. Annual Review of Fluid Mechanics 17(1):91-118. https://doi.org/10.1146/annurev.fl.17.010185.000515

[5] Dobias B, Schick MJ, Fowkes FM, Dekker M (1993) Coagulation and flocculation: theory and applications. Surfactant Science Series: Journal of Chemical Education 70(7):A199. https://doi.org/10.1021/ed070pA199.9

[6] Gibbs RJ (1983) Coagulation rates of clay minerals and natural sediments. Journal of Sedimentary Research 53(4):1193-1203. https://doi.org/10.1306/212f8341-2b24-11d7-8648000102c1865d

[7] Imai G (1981) Experimental studies on sedimentation mechanism and sediment formation of clay materials. Soils and Foundations 21(1):7-20. https://doi.org/10.3208/sandf1972.21.7

[8] Kobayashi S, Adachi Y (2008) Analysis of na- and ca-montmorillonite floc structure. Transactions of The Japanese Society of Irrigation, Drainage and Rural Engineering

2008(253):21-26. https://doi.org/10.11408/jsidre2007.2008.21 (in Japanese with English abstract)
[9] Kynch GJ (1952) A theory of sedimentation. Transactions of the Faraday Society. 48:166–176. https://doi.org/10.1039/TF9524800166
[10] Michaels AS, Bolger JC (1962) Settling rates and sediment volumes of flocculated kaolin suspensions. Industrial & Engineering Chemistry Fundamentals 1(1):24-33. https://doi.org/10.1021/i160001a004
[11] Miyahara K, Adachi Y, Nakaishi K (1998) The viscosity of a dilute suspension of sodium montmorillonite in an alkaline state. Colloids and Surfaces A: Physicochemical and Engineering Aspects 131(1-3):69-75. https://doi.org/10.1016/S0927-7757(96)03961-1
[12] Miyahara K, Adachi Y, Nakaishi K, Ohtsubo M (2002) Settling velocity of a sodium montmorillonite floc under high ionic strength. Colloids and Surfaces A: Physicochemical and Engineering Aspects 196(1):87-91. https://doi.org/10.1016/S0927-7757(01)00798-1
[13] Nakaishi K, Ooi S, Kobayashi M (2012) Effects of container diameter and volume fraction on the sedimentation process of flocculated clay suspensions. Journal of the Society of Rheology, Japan 40(4):205-208. https://doi.org/10.1678/rheology.40.205
[14] Nanzyo M, Kanno H (2018) Inorganic constituents in soil. Springer Singapore, Singapore
[15] Pope SB (2000) Turbulent flows. Cambridge University Press, Cambridge
[16] Richardson JF, Zaki WN (1954) Sedimentation and fluidization: Part I. Transactions of the Institution of Chemical Engineers. 32:35-53. https://doi.org/10.1016/S0263-8762(97)80006-8
[17] Sudo M, Miki T, Masuda Y (2009) Research on characteristics of turbid water effluent from paddy fields during the paddling and the transplanting period. Transactions of The Japanese Society of Irrigation, Drainage and Rural Engineering 77(2):113-119. https://doi.org/10.11408/jsidre.77.113 (in Japanese with English abstract)
[18] Sueto J, Nakaishi K (1992) Thixotropic behaviors of sodium and calcium montmorillonites at salt concentrations in the vicinity of 0.3 n. Clay Science 8(6):349-353. https://doi.org/10.11362/jcssjclayscience1960.8.349
[19] Tombácz E, Gilde M, Ábrahám I, Szántó F (1988) Effect of electrolyte concentration on the interaction of humic acid and humate with montmorillonite. Applied Clay Science 3(1):31-52. https://doi.org/10.1016/0169-1317(88)90004-X
[20] Uddin F (2008) Clays, nanoclays, and montmorillonite minerals. Metallurgical and Materials Transactions A 39(12):2804-2814. https://doi.org/10.1007/s11661-008-9603-5
[21] Wakai T, Kaneki R, Itakura Y, Banno M (2005) Water quality and loads of rivers during puddling transplanting period. Journal of Japan Society of Hydrology & Water Resources 18(2):167-176. https://doi.org/10.3178/jjshwr.18.167 (in Japanese with English abstract)
[22] Winterwerp JC, Kestern WGMV (2004) Introduction to the physics of cohesive sediment in the marine environment. Elsevier, Amsterdam
[23] Wu M, Adachi Y (2016) Effects of electrolyte concentration and pH on the sedimentation rate of coagulated suspension of sodium montmorillonite. Colloids and Surfaces A: Physicochemical and Engineering Aspects 506(2016):686-693. https://doi.org/10.1016/j.colsurfa.2016.07.027

[24] Wu M, Adachi Y (2018) Duration of initial flocculation stage in the sedimentation of sodium montmorillonite suspension in the semi-dilute regime. Colloid and Polymer Science 296(1):71-76. https://doi.org/10.1007/s00396-017-4222-6

Figure 1

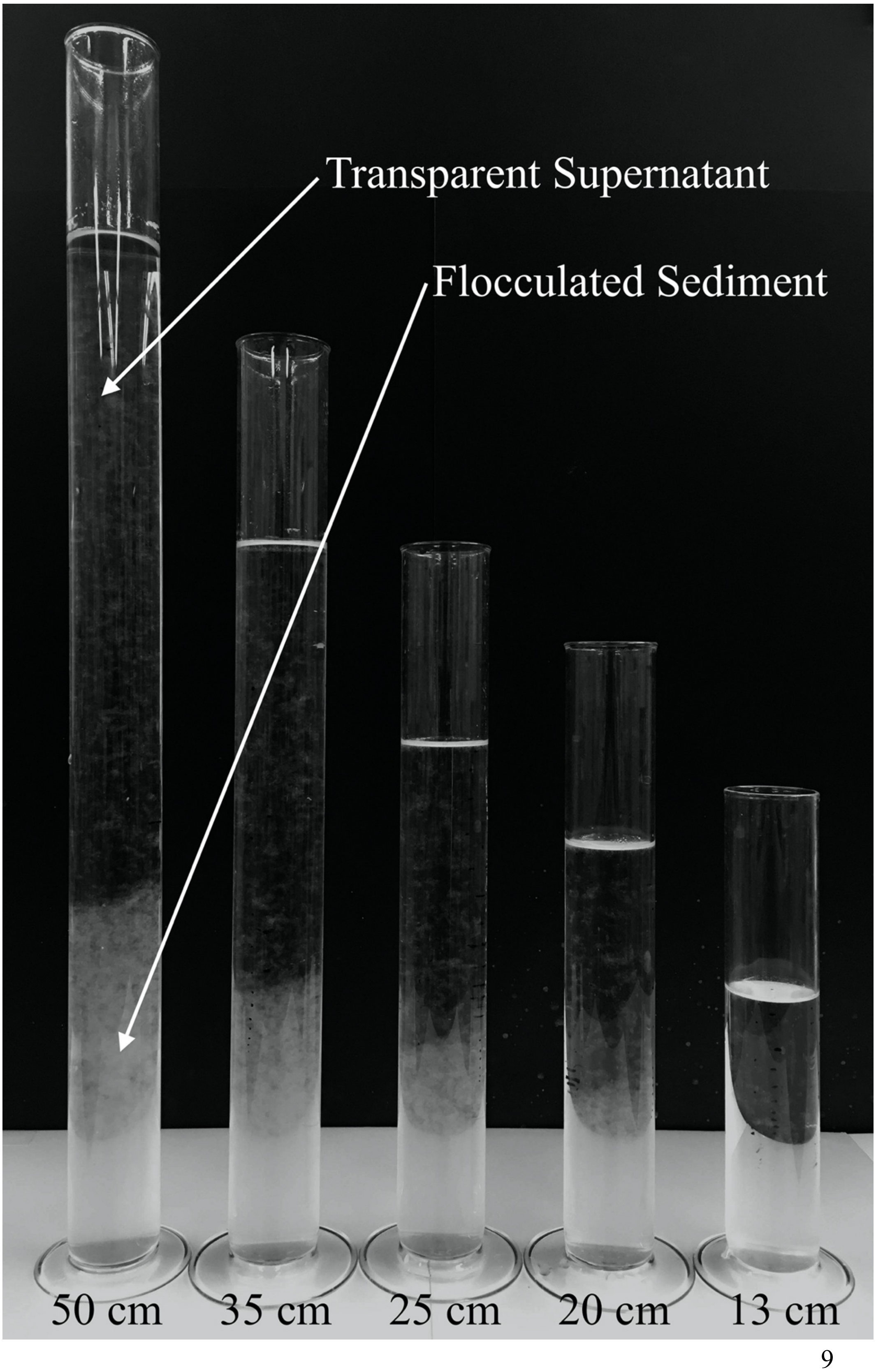
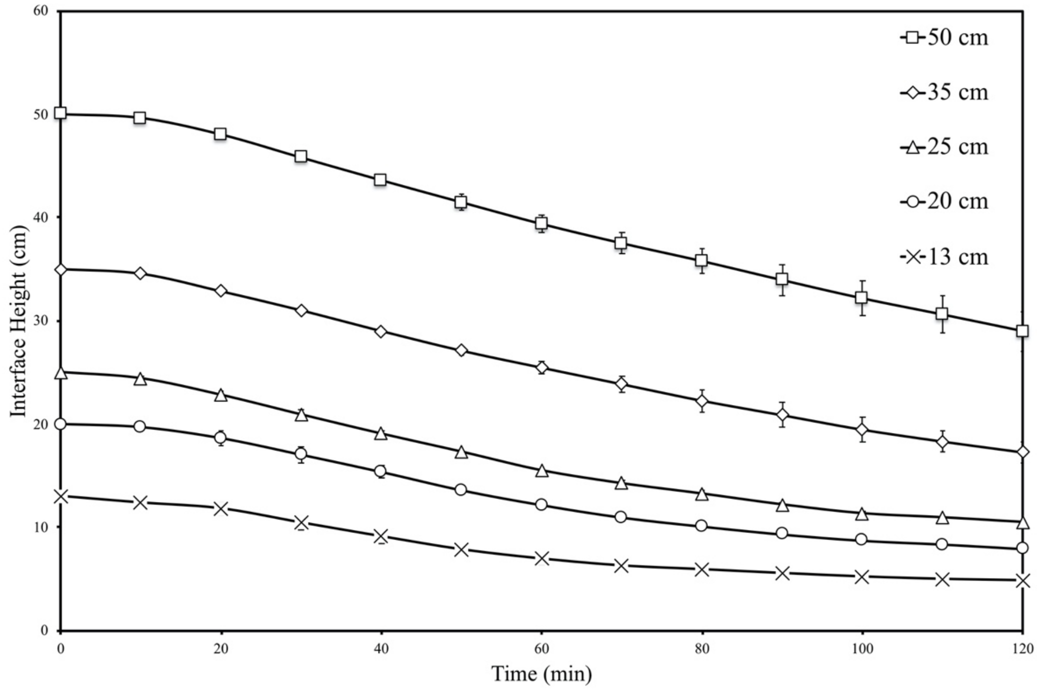
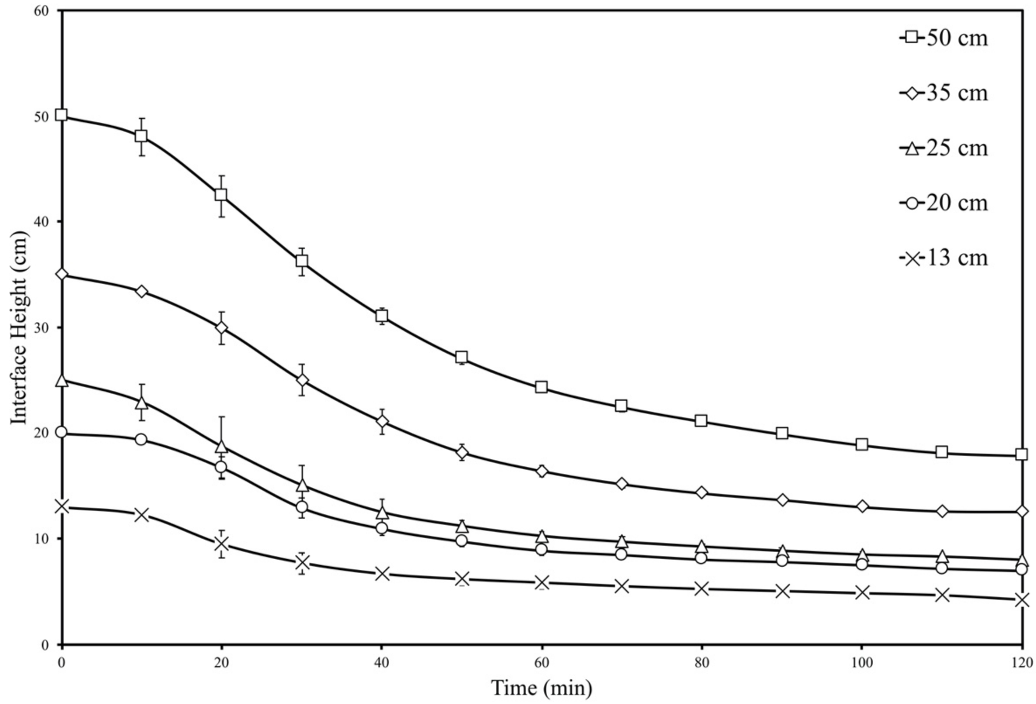


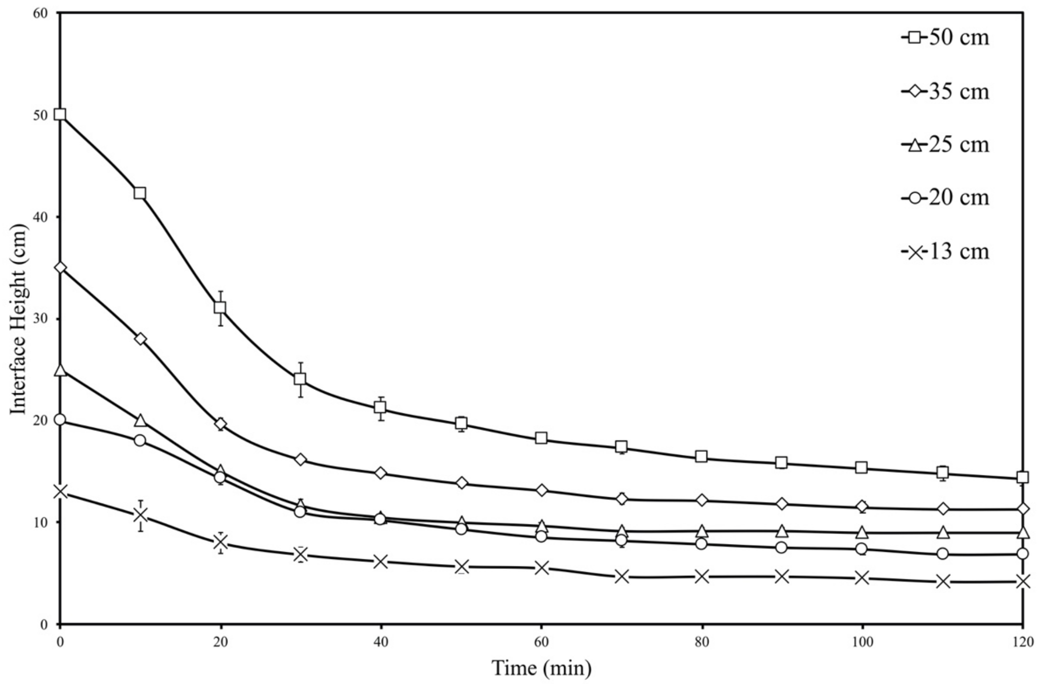
Figure 2a-e



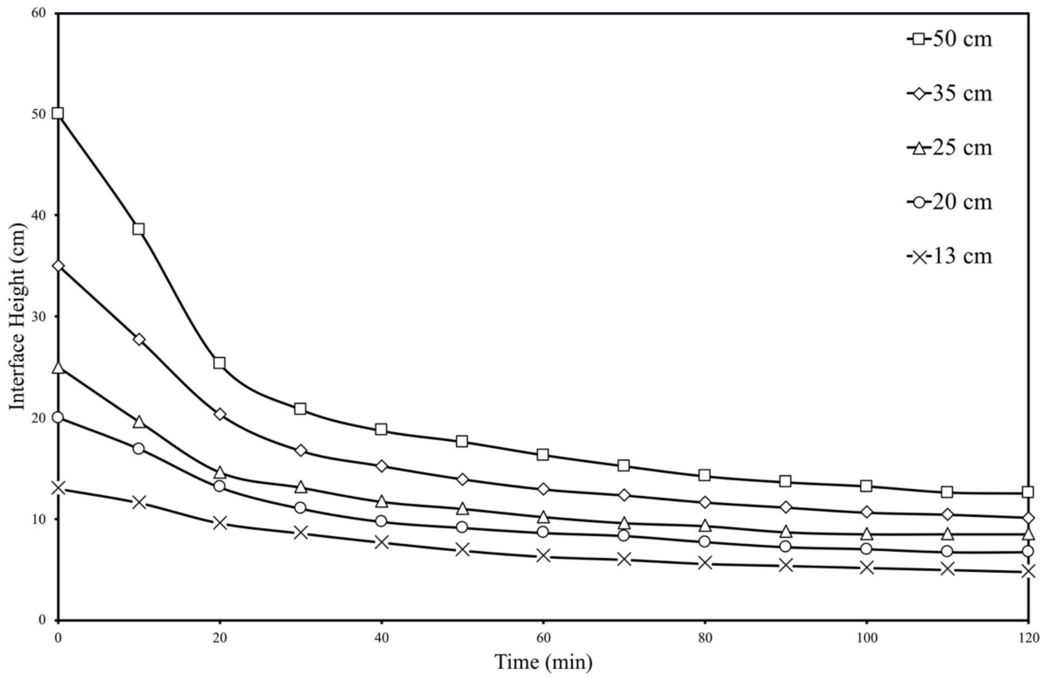
50 cm
35 cm
25 cm
20 cm
13 cm
Interface Height (cm)
Time (min)
0
10
20
30
40
50
60
0
20
40
60
80
100
120



50 cm
35 cm
25 cm
20 cm
13 cm
Interface Height (cm)
Time (min)
0
10
20
30
40
50
60
0
20
40
60
80
100
120

307 

60
50
40
30
20
10
0
Interface Height (cm)
0
20
40
60
80
100
120
Time (min)
50 cm
35 cm
25 cm
20 cm
13 cm

308 

60
50
40
30
20
10
0
Interface Height (cm)
0
20
40
60
80
100
120
Time (min)
50 cm
35 cm
25 cm
20 cm
13 cm

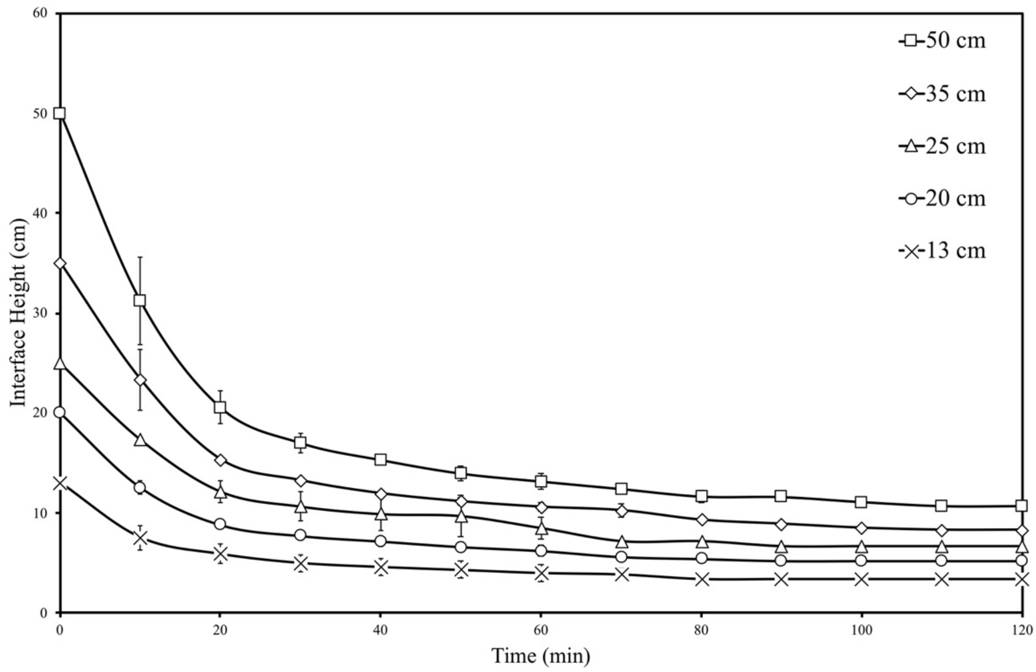


Figure 3

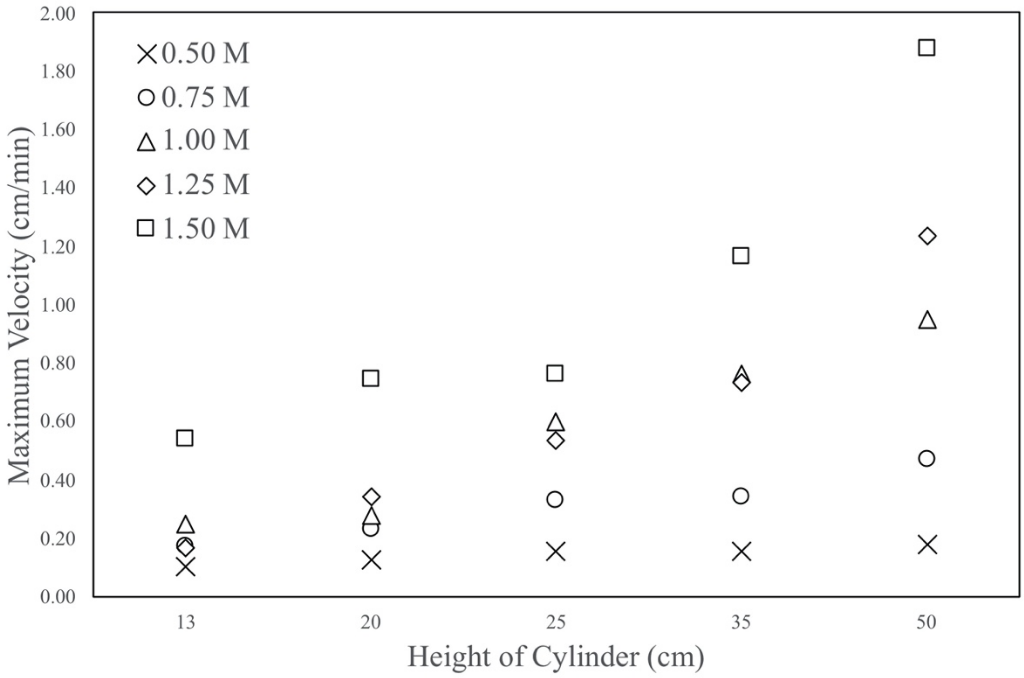


Figure 4

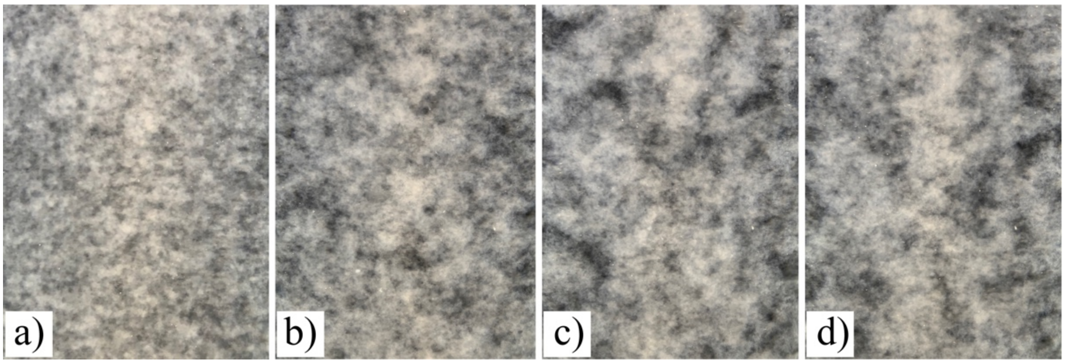


Figure 5

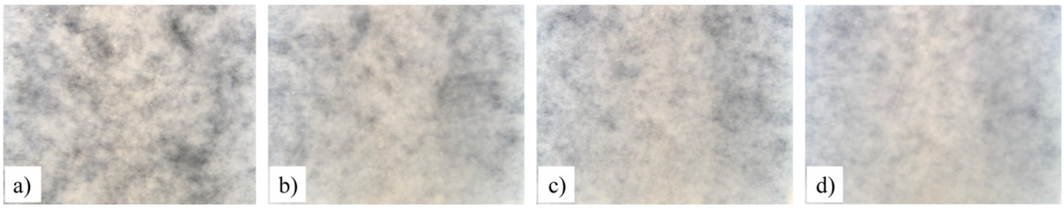


Figure 6

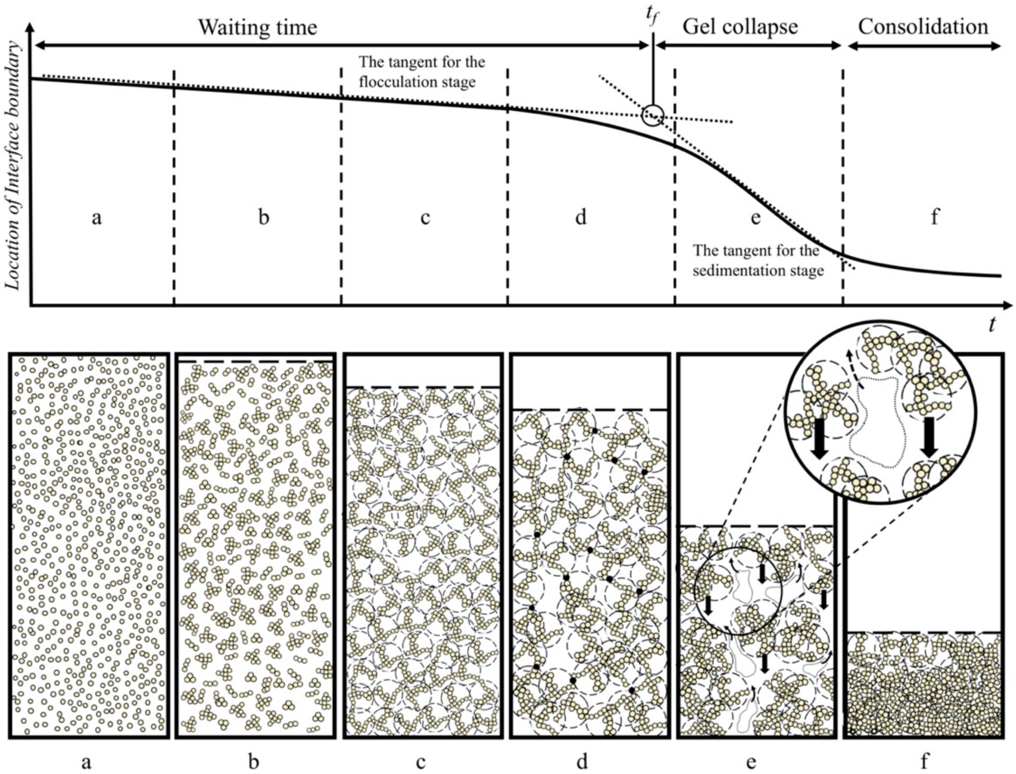


Figure Caption

Figure 1	Clear interface boundary between flocculated sediment and the transparent supernatant in different cylinder height
Figure 2	Interface height as function of elapsed time for different levels of ionic strength, with error bars representing the standard deviations; a) 0.5 M, b) 0.75 M, c) 1.0 M, d) 1.25 M and e) 1.5 M
Figure 3	Maximum velocity as function of cylinder height at different levels of ionic strength
Figure 4	Flocculation and settling stage of Na-Montmorillonite at 20 cm of cylinder height over time; a) 1 minute, b) 5 minutes, c) 9 minutes and d) 12 minutes
Figure 5	Consolidation stage of Na-Montmorillonite at bottom of 15 cm cylinder over time; a) 14 minutes, b) 16 minutes, c) 30 minutes and d) 42 minutes
Figure 6	Schematic representation explaining the progress of sedimentation of flocculated materials in the semi-dilute regime. a) Just after mixing, uniform dispersion is formed. b) Small flocs are formed and suspended independently. At this stage, we can already identify the clear interface boundary between the flocculated sediment and the transparent supernatant. It starts to settle down slowly. The rate of sedimentation is very small reflecting the small size of flocs. During this stage, the flocculation process is ongoing. c) The space-filling structure of sediment is formed. d) At some contacting points in the network (marked as black circles), the stress is concentrated due to self-weight of the sediment. The point will resist against the compression by self-weight of the network. Due to this resistance, the apparent sedimentation rate is essentially low. Once the network could no longer yield the stress, the network starts to break down and mark the onset of gel collapse. The intersection point for tangents of linear parts between the flocculation stage and sedimentation stage with maximum sedimentation rate is denoted as the flocculation time, t_f. e) Abrupt gel collapse during this stage initiate the rapid sedimentation stage. Development of crack void while flocs fall down during gel collapse created the water channelling in the network. Downward motion of flocculated sediment (represented by big arrows) will induce the generation of upward plume of water (represented by small arrows) which is a bit fluttering. In the high cylinder, the traveling distance of falling flocs become

	longer. The development of flocs along the long traveling distance coupled with the sedimentation turbulence creates a feed-forward mechanism which further enhanced the sedimentation process. f) Flocs are accumulated at the bottom and consolidate very slowly.