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Analysing the segregation of coarse tailings particles with a zone-formation differential settling model

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Abstract

This study delves into the segregation and settling behaviours of tailings suspensions with varying initial solids contents, with a specific focus on the initial segregation process. Conventional and interruptive batch settling tests were performed to evaluate the hindered settling process of copper tailings. During these tests, particular attention was paid to the differential settling behaviour at the initial stage, during which coarse particles segregated from the suspension and accumulated at the bottom. The particle size distribution profile of the suspension was analysed in detail, revealing that segregation was a prevalent phenomenon in all settling tests. To perform a theoretical analysis of this segregation behaviour, a zone-formation differential settling model was introduced and applied, allowing a detailed discussion of the settling behaviour of individual particle species. Consequently, the findings offer insights into the variation of the segregation behaviour and formation of the sediment under different initial conditions. Suggestions are also provided for the application of the zone-differential settling model on the sedimentation of tailings which contains fine particle species.

Keywords: *sedimentation, zone-formation differential settling, segregation, tailings*

1 Introduction

Throughout the different stages of tailings management, the sedimentation phenomenon of tailings particles is a common occurrence. This includes activities such as tailings dewatering operation, the deposition and storage of tailings, and tailings backfilling. In recent years, there has been an increasing number of studies on tailings suspensions, aiming to delve into the underlying principles of the settling process (Bonin et al. 2019; Peng et al. 2020; MacIver et al. 2021; Li 2023). In the sedimentation of diverse types of tailings, the segregation of particles – which is characterized by particles settling at different velocities – can be frequently encountered, resulting in unexpected consequences. Therefore, understanding the fundamentals of the differential settling behaviours and modes of tailings suspensions can benefit our comprehension on various phenomena associated with the sedimentation of tailings.

The sedimentation of solid–liquid systems has been a subject of study for over a century. A common experimental method to investigate sedimentation involves conducting batch settling tests using a clear graduated cylinder or column filled with suspension. Coe & Clevenger (1916) conducted batch settling tests on slime suspensions, revealing the classification of zones within the suspension experiencing hindered settling. Subsequently, Kynch (1952) developed the theory of sedimentation, which became a highly influential approach in addressing hindered settling in suspensions of equal-sized particles (monodisperse suspension). Kynch employed a continuity equation for mass balance and a flux curve as the constitutive relationship to model the hindered settling process. From Kynch theory, various settling modes can be interpreted based on different initial conditions. Figure 1 depicts the batch settling interpretation of the simplest settling mode generated from Kynch theory, illustrating both the settling curve and the zone classification within the suspension. The associated settling behaviour is typical and representative of the sedimentation observed in a wide range of materials.

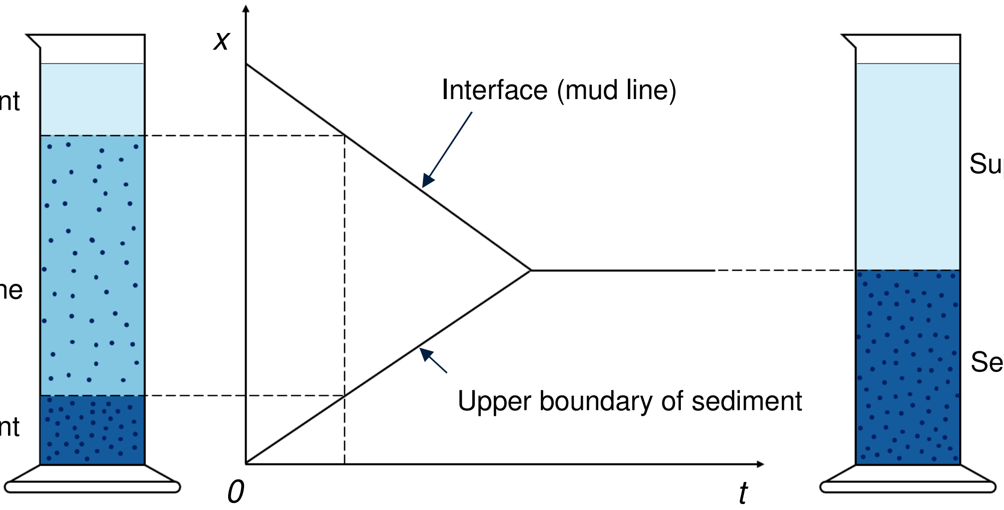


Figure 1 **The simplest settling mode interpreted from Kynch theory**

The application of Kynch theory becomes less effective when dealing with tailings suspensions that encompass a wide range of particle sizes, primarily because the physical model fails to meet the original assumptions of the theory. When larger particles within tailings suspensions settle at higher velocities, it leads to what is known as differential settling. The simplest form of this settling phenomenon is seen in binary suspensions. Smith (1965) studied the settling behaviour of suspensions containing two particle sizes of equal density. He observed differential settling, where larger particles settled at a higher velocity, creating a zone in the settling region containing only smaller particles.

In 1979, several research groups developed the settling velocity model for polydisperse suspensions (Masliyah 1979; Lockett & Bassoon 1979; Mirza & Richardson 1979). In systems containing particles of multiple sizes, these particles are classified into distinct fractions or species based on their sizes. During batch settling, each particle species settles at its specific velocity in the suspension. Due to the velocity difference, each species has a corresponding ‘settling curve’ marked by the trajectory of the slowest-settling particle of this species. This results in various settling zones within the hindered settling region and sediment. The settling curves and settling zones are depicted in Figure 2. These zones contain different particle species, with boundaries determined by the last settling particle of each species. The local solids concentration within each zone is the cumulative concentration of all the particle species it contains.

To quantitatively analysis the settling behaviour of a multi-sized particle suspension, Lockett & Bassoon (1973, 1979) first formulated the zone-formation differential model. Mirza & Richardson (1979) used a similar model to account for the differential settling of both binary and multi-sized particle suspensions. Their differential settling models a simplistic representation of the settling behaviour wherein each particle species settles in a way described in Figure 1. Greenspan & Ungarish (1982) expanded their study to develop settling models for multi-sized particle suspensions with discrete and continuous size distributions. Concha et al. (1992) extended Kynch theory to accommodate the differential settling of multi-sized particle suspensions. However, they didn't provide a general sedimentation mode for differential settling due to the lack of an analytical solution for the continuity equations.

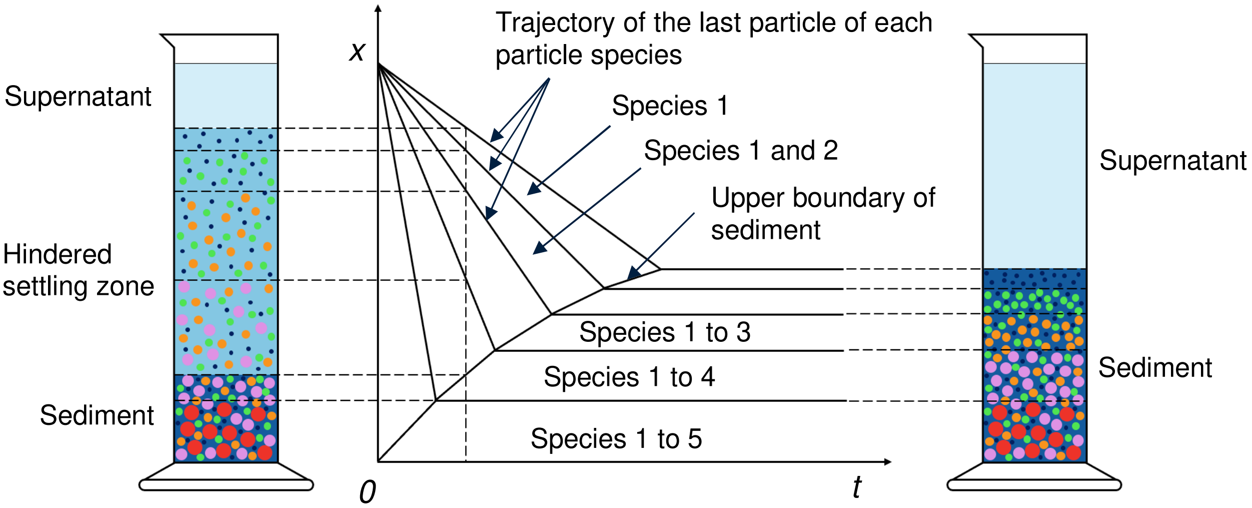


Figure 2 **Zone-formation differential settling behaviour**

The zone-formation differential settling model is a valuable tool for understanding the overall settling behaviour of multi-sized particle suspensions from a mathematical viewpoint. However, its practical application in engineering confronts challenges, particularly in particle species classification, determining their settling velocities, and assessing maximum solids content. In certain circumstances of tailings sedimentation, the differential settling behaviour might not be pronounced or might only apply to the coarser fraction of the tailings particles. Recent experimental studies conducted by Li & van Zyl (2022, 2023) showcased the initial segregation of coarse particles at the early stage of batch settling of copper tailings. Subsequently, although some continuous segregation of particles persisted, the differential settling phenomenon was observed to be minimal. In such a case, it may be reasonable to only consider the differential settling behaviour of specific coarse particles when investigating the sedimentation of the tailings suspension.

Hence, it becomes crucial to conduct an assessment on the suitability of applying the zone-formation differential settling model to the sedimentation of tailings. In this paper, we qualitatively discuss the settling behaviour of tailings containing coarse particles, focusing on the application of the zone formation differential settling model. This examination aims to provide insight into the behaviour of such tailings, considering the potential limitations and applicability of the differential settling model in this context.

2 Settling velocity model and differential settling model

In the batch settling process of a multi-sized suspension comprising m particle species (ranging from size 1 to size m), the settling region of the suspension forms m distinct settling zones, in addition to the supernatant and sediment (refer to Figure 3), as the settling process initiates. The topmost zone (referred to as zone 1 in Figure 3) exclusively contains particles of the smallest size (size 1). Conversely, the bottommost zone (referred to as zone m in Figure 3) encompasses particles ranging from the smallest (size 1) to the largest (size m). The total solids content within a particular zone corresponds to the sum of the solids concentration of all particle species it contains. These zones are classified based on the movement of the last particle belonging to the largest species within each zone. For a given particle species i in zone k, the settling velocity is denoted by $v_{i,k}$ (where i ≤ k). The settling velocity at the boundary separating zone k-1 and zone k, denoted as u_k, is equivalent to $v_{k,k}$.

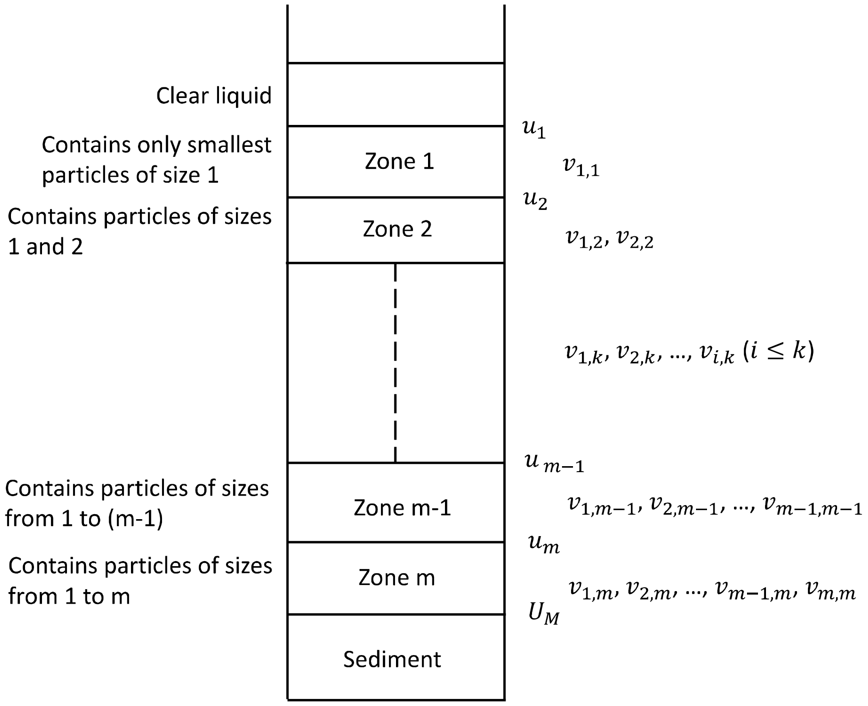


Figure 3 Zone-formation differential settling model

In batch settling, the total flux of the system is equal to zero, which leads to the following relationship for the suspension in a specific settling zone in the column:

$$\sum_{i=1}^{k} v_{i,k}\varphi_{i,k} + v_{f,k}\left(1-\sum_{i=1}^{k}\varphi_{i,k}\right) = 0 \tag{1}$$

where:

$\varphi_{i,k}$ = solids concentration of particle species i in zone k

$v_{i,k}$ = settling velocity of particle species i in zone k

$v_{f,k}$ = fluid velocity in zone k.

The difference between the settling velocity of the particles and the fluid velocity is termed the slip velocity (relative velocity) of the particles. For a specific particle species, the slip velocity can be represented as a product of the terminal falling velocity of a single and a function of the total solids concentration (Lockett & Bassoon 1979; Mirza & Richardson 1979). Various empirical and semi-empirical equations exist for this representation. However, for the sake of general applicability, expressing the slip velocity as a function of the total solids concentration is preferred to maintain generality (Equation 2).

$$v_{i,k} - v_{f,k} = v_{i,k}^{s} = v_{\infty i}\Phi\left(\sum_{i=1}^{k}\varphi_{i,k}\right) = v_{\infty i}\Phi(\varphi_{Tk}) \tag{2}$$

where:

$v_{i,k}^{s}$ = slip velocity of particle species i in zone k

$v_{\infty i}$ = Stokes terminal falling velocity of particle species i

Φ = a function of total solids concentration of all particle species

φ_{Tk} = total solids concentration of all particle species in zone k.

Combining Equations 1 and 2, the velocity model of a specific particle species in a settling zone can be derived:

$$v_{i,k} = v_{i,k}^{s} - \sum_{i=1}^{k} v_{i,k}^{s}\varphi_{i,k} = v_{\infty i}\Phi(\varphi_{Tk}) - \sum_{i=1}^{k} v_{\infty i}\Phi(\varphi_{Tk})\varphi_{i,k} \tag{3}$$

In the differential settling scenario depicted in Figure 3, when a zone k comes into contact with the advancing boundary of the sediment, the particle species within that zone settle directly into the sediment. This settling behaviour aligns with the simplest Kynch settling mode demonstrated in Figure 1, which has been adopted by a number of researchers in their differential settling models (Lockett & Bassoon 1979; Mirza & Richardson 1979; Selim et al. 1983). At the boundary between zone k and the sediment, there exists a relationship that ensures mass balance for each particle species i.

$$(U_k - v_{i,k})\varphi_{i.k} = (U_k - v_{i,M})\varphi_{i,M} \tag{4}$$

where:

U_k = propagation velocity of the boundary between zone k and sediment

$v_{i,M}$ = settling velocity of particle species i in the sediment

$\varphi_{i,M}$ = the maximum solids concentration of the particle species i in the sediment.

The physical interpretation of this relationship implies that the quantity of particles entering the boundary equals the total quantity of particles exiting from the boundary. Equation 4 offers flexibility in its application to determine the variables involved in various ways.

3 Experimental program

3.1 Tailings samples and experimental apparatus

In the experimental program, a copper tailings was chosen due to its wide range of particle species, ensuring the occurrence of differential settling. The specific gravity of these copper tailings is measured at 2.72. The cumulative and differential particle size distribution (PSD) curves of the sample, obtained using Malvern Mastersizer, are both depicted in Figure 4.

To investigate the suspension's differential settling behaviour, it's crucial to have profiles detailing the local solids concentration and PSD. While determining the suspension's solids concentration during a batch settling test can be achieved through various techniques like X-ray approach, gamma-ray approach, or pressure measurements, acquiring the PSD of samples at different heights in a batch settling column requires direct sampling (Benn et al. 2018). As a result, interruptive settling tests were performed on copper tailings samples utilising a specially designed experimental apparatus (Figure 5). For an understanding of the sample collection process and the dimensions of the settling column, refer to Figure 6. For detailed insights into the procedural aspects of an interruptive test, please refer to the paper authored by Li & van Zyl (2023).

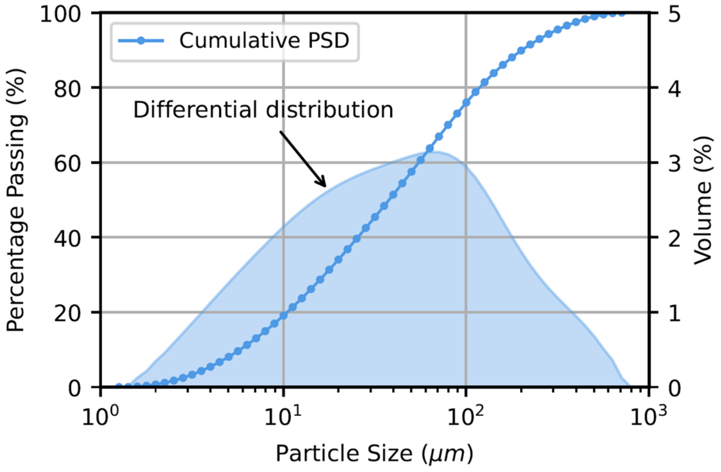


Figure 4 Original particle size distribution (PSD) curves of the copper tailings

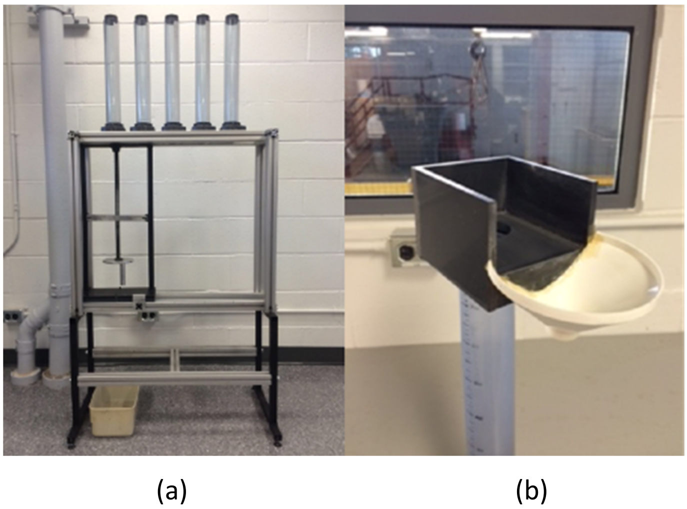


Figure 5 **A photo of the experimental apparatus. (a) The settling columns; (b) The top piece for sample collection (Li 2023)**

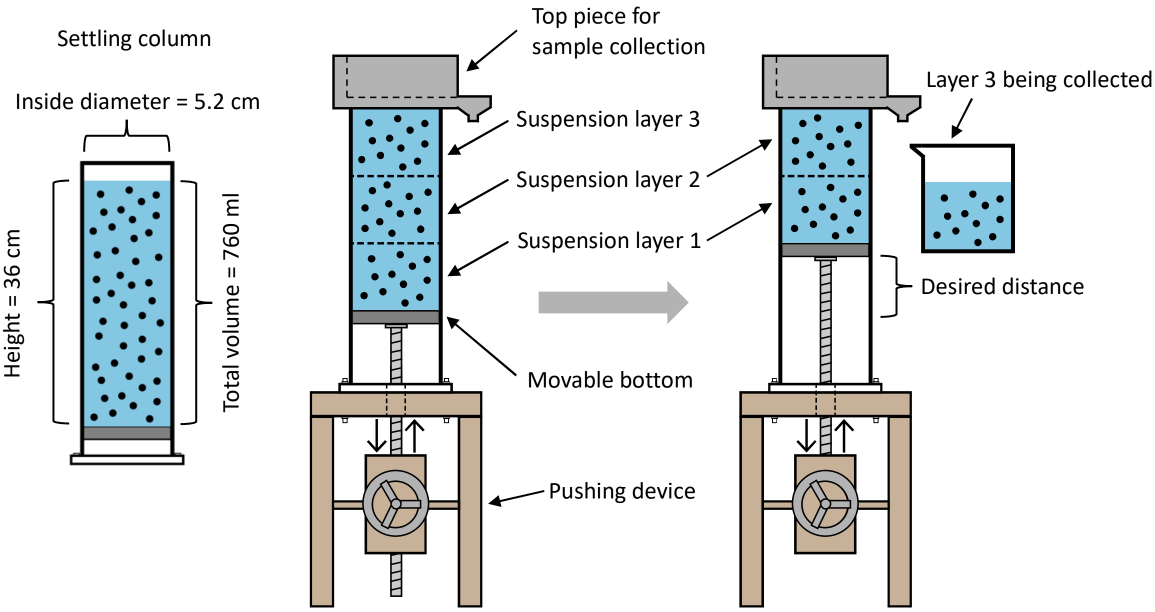


Figure 6 **Illustration of the tailings sample collection procedure (Li & van Zyl 2023)**

3.2 Experimental methodology

For the experimental investigation, six distinct tailings suspensions with varying initial solids content (measured as a solids percentage by weight) were prepared by mixing the dried tailings particles with deionized water. For each suspension, two types of tests were conducted: a conventional batch settling test and an interruptive batch settling test. These tests were carried out to generate the settling curve and gather samples for analysis. During the interruptive tests, the recording of the settling time concluded when the interface between the supernatant and suspension reached a height of 34 cm. Following the cessation of the settling process, samples were collected. The settling time of each tailings suspension is summarised in Table 1. Subsequently, the collected samples from the suspension underwent drying in an oven to determine the solids content. Additionally, the PSD of these samples was determined to facilitate further discussion and analysis.

Table 1 **Summary of the interruptive batch settling tests**

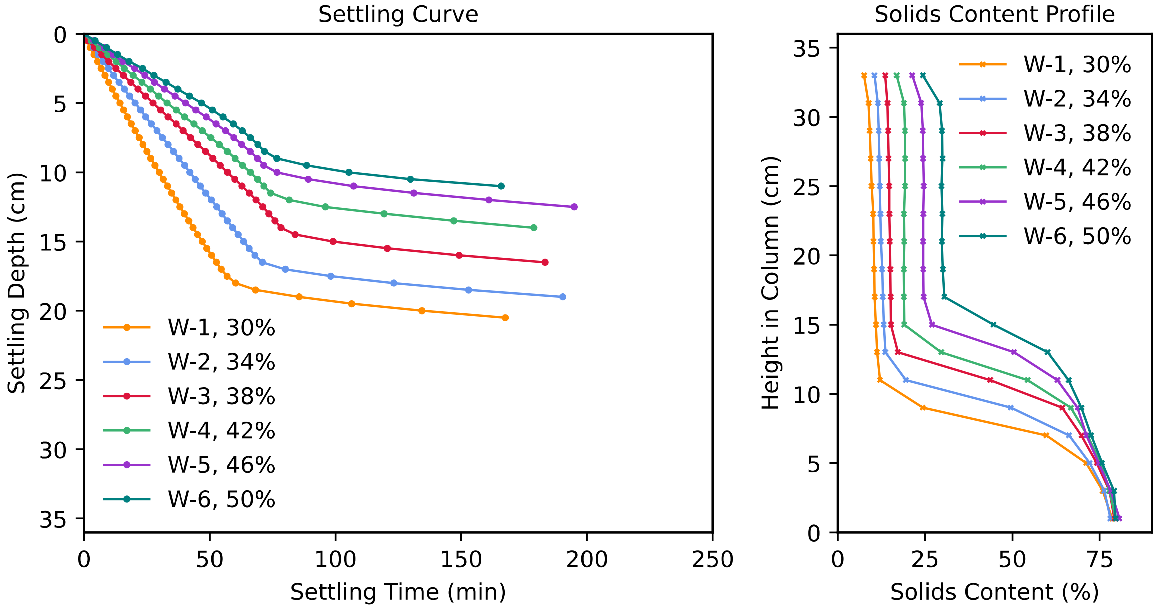
Test no.	Solids content	Settling time	Number of samples collected
W-1	30%	5 min 20 sec	17
W-2	34%	7 min 50 sec	17
W-3	38%	9 min 50 sec	17
W-4	42%	13 min 10 sec	17
W-5	46%	17 min 15 sec	17
W-6	50%	18 min 30 sec	17

4 Result and discussion

4.1 Settling curve

The overall settling curves for all six suspensions are shown in Figure 7a. Settling curves conventionally serve as valuable tools for analysing the general settling behaviour of suspensions, especially concerning monodisperse suspension sedimentation. Generally, the settling curves in Figure 7a exhibit a two-phase shape, similar to the settling curve illustrated in Figure 1. This shape signifies the occurrence of hindered settling during the initial phase of the settling process, distinguished from compression settling (another settling mode). In a typical hindered batch settling process, a hindered settling zone usually forms beneath the supernatant–suspension interface. Analysis of the settling curves from Figure 7a indicates that hindered settling predominates when the solids content ranges from 30 to 50%.

However, when examining the differential settling behaviour of the suspension, the settling curve lacks crucial information. In the differential settling mode displayed in Figure 2, the settling curve only depicts the movement trajectory of the smallest particle species, offering no insights into the relative movements of other particle species. For a more comprehensive understanding of the differential settling behaviour, utilizing solids content profiles and PSD profiles proves to be more effective. These profiles offer detailed information regarding the differential settling behaviour of various particle species within the suspension.



(a) (b)

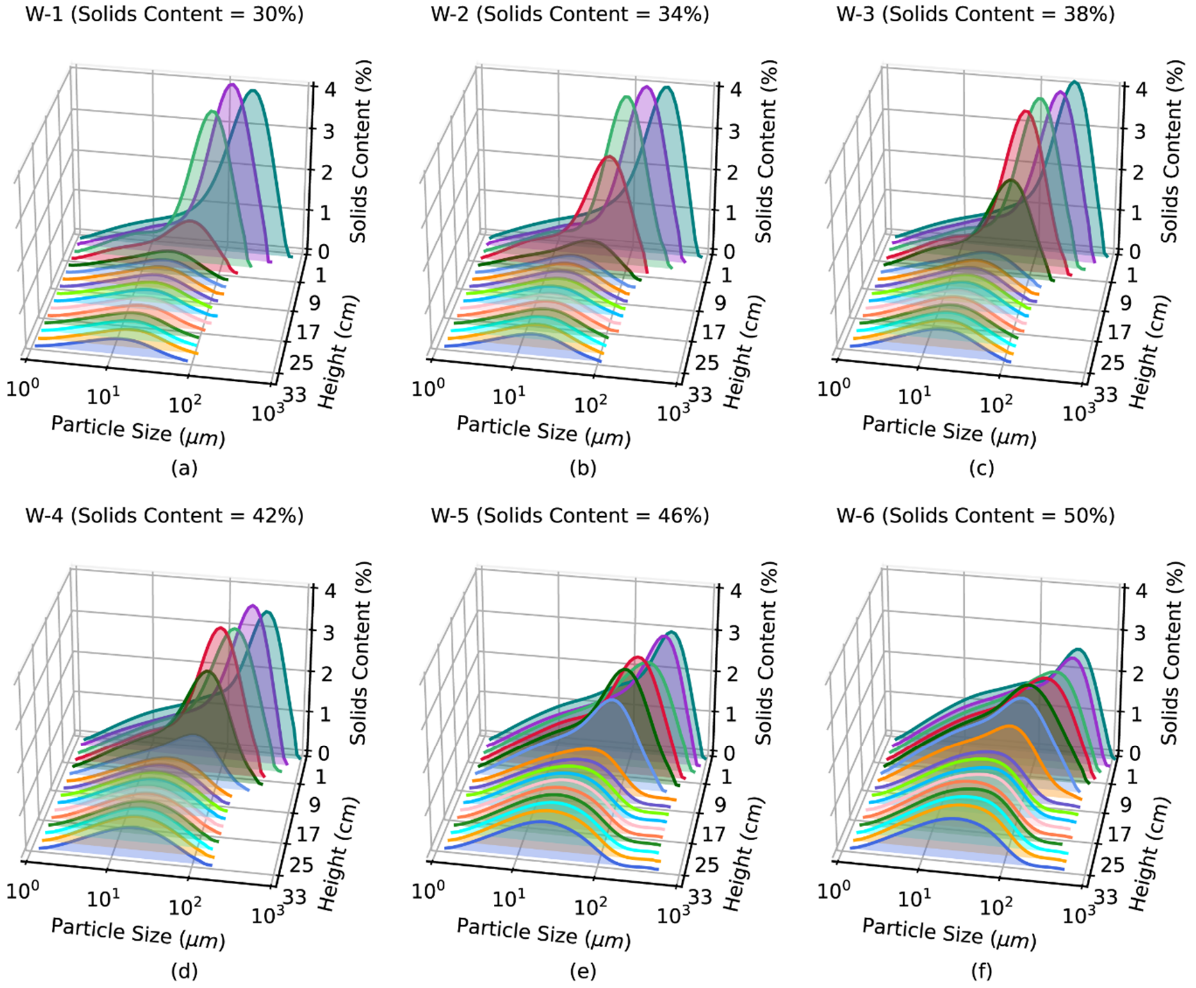
Figure 7 **Experimental results of batch settling tests. (a) Settling curve; (b) Solids content profile**

4.2 Solids content of particle species

The solids content profile is depicted in Figure 7b. In the upper region of the suspension, a uniform solids content is observed, reflecting the hindered settling zone as indicated by the initial phase of the settling curve. The existence of this hindered settling zone aligns with theoretical predictions from the Kynch settling mode and has been validated through batch settling tests conducted on various materials.

Nevertheless, the local solids contents observed within the hindered settling zones in this study were notably lower than the initial values. It can be reasonably speculated that the reduction in solids content might be attributed to the differential settling or segregation of coarse particles. Additionally, the significant increase in solids content observed in the sediment at the bottom could potentially be due to the accumulation and concentration of coarse particles. However, further validation is required as the sedimentation process itself can also lead to an increase in solids content. It's worth noting that the solids content corresponding to the sediment at the bottom changes with height, a phenomenon that is not explicitly addressed in any existing types of settling models.

To gain direct insight into the settling behaviour of particles, PSD analyses were conducted on samples collected during the interruptive settling tests. Based on the results, an adjusted three-dimensional differential PSD curve was generated, depicted in Figure 8. This specialised plot integrates the original differential PSD curves with corresponding solids content profiles. Within this adjusted plot, the vertical axis (solids content) illustrates the solids weight percentage of particles of a specific size species concerning the total weight. The height axis depicts the position where each sample was collected.



(a) (b) (c)

(d) (e) (f)

Figure 8 Adjusted three-dimensional differential particle size distribution curves

Figure 8 provides a clear visualisation of particle composition and associated solids content. The variations in the adjusted PSD curve validate the differential settling behaviour of the suspension. Notably, samples collected from the upper region of the suspension exhibit an absence of coarse particles compared to those collected at the bottom. This observation suggests the segregation of coarse particles at the time of sample collection. Examining results from tests W-1 to W-4 in Figure 8 underscores that the increased solids content in the lower suspension area is primarily attributed to the segregation of coarse particles, despite the observable sedimentation of the finer particle species.

To effectively integrate the zone-formation differential settling model into the discussion of the experimental outcomes, a vertical stack plot was constructed (Figure 9). Within this plot, particles were categorised into six species (A, B, C, D, E, and F) based on their respective particle sizes. The particle size ranges span from 0–10, 10–20, 20–40, 40–80, 40–80, and 160+ µm, progressively ascending from small to large sizes. The local solids content of each particle species was calculated utilizing the PSD data and the solids content profile. Stacking of the solids content occurs along the vertical axis, representing the height of the settling column. This stack plot enables a direct comparison of the solids content for each particle species at various heights. Consequently, the settling behaviour of each particle species can be conveniently observed. The dashed line in each subplot denotes the initial solids content of the suspension prior to sedimentation. The outcomes illustrated by Figure 9 suggest that the differential settling process of certain coarse particle species has reached completion (coarse particles have settled into the sediment) by the time of sampling. Interestingly, there is no apparent settling zone observed within the hindered settling region, as shown in Figure 3.

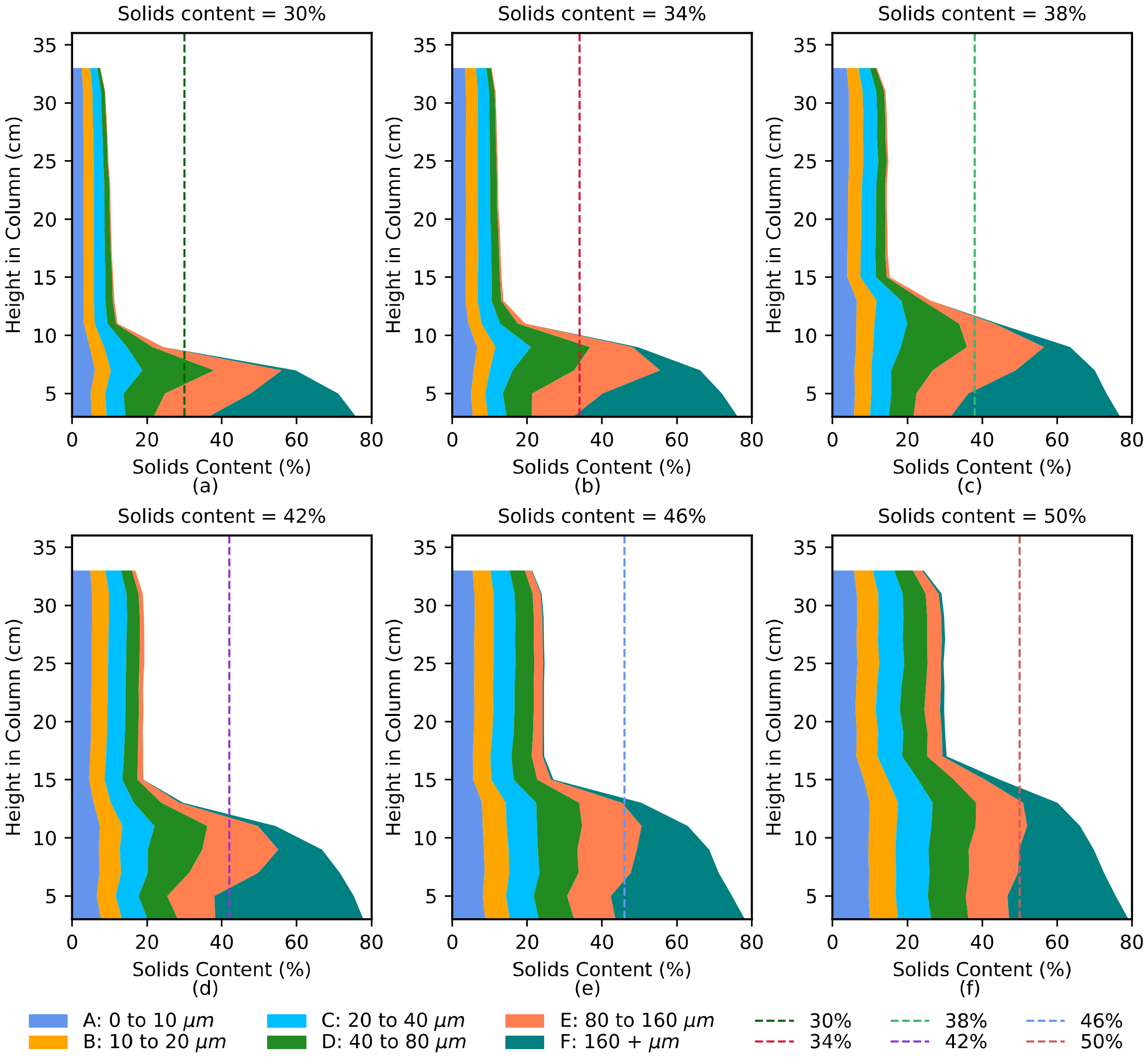


Figure 9 **Solids contents of particle species under different initial conditions**

4.3 The zone-formation differential settling behaviour

4.3.1 Classification of the particle species

According to Figure 9, the hindered settling zone contains several particle species, exemplified by the 38% suspension. Evidently, within this hindered settling zone, particle species A, B, and C coexist, displaying uniform solids content along the settling direction. This outcome indicates that these three particle species settled together at the same velocity within the hindered settling zone. However, referencing the settling velocity model described by Equation 3, there should theoretically be different settling velocities for particle species A, B, and C within the uniform hindered settling zone due to their different corresponding Stokes terminal falling velocities (attributed to varying particle sizes). This discrepancy highlights the significance of the particle species classification in the differential settling model, indicating that arbitrary classification of particle species might not be ideal. Li & van Zyl (2022) proposed the concept of a hinderance force resulting from the aggregation of the particles (it is important to clarify that the particle aggregation discussed in this paper refers to the phenomenon where particles adhere to each other due to van der Waals and other inter-particle forces to form clusters and flocs). The consideration of this force may result in small particles sticking together, settling as a collective entity. Thus, fine particles within a certain size range could potentially be considered as a single particle species when employing the zone-formation differential settling model. The specific range of fine particles classified as one species varies among suspensions, influenced by factors such as initial solids content, PSD of the suspension, and its chemical properties. Observing Figure 9a, the hindered settling zone solely comprises particle species A, B, and C. However, in suspensions with a solids content of 50%, the hindered settling zone encompasses particle species A, B, C, D, and E, demonstrating the variability based on different initial solids content values.

4.3.2 Relative velocity between particle species

A qualitative comparison of the settling velocity difference between two particle species in the differential settling model can be achieved using Equation 5, which calculates the ratio of settling velocities for species 1 and 2.

$$\frac{v_{1,k}}{v_{2,k}} = \frac{v_{\infty 1}\Phi(\varphi_{Tk}) - \sum_{i=1}^{k} v_{\infty i}\Phi(\varphi_{Tk})\varphi_{i,k}}{v_{\infty 2}\Phi(\varphi_{Tk}) - \sum_{i=1}^{k} v_{\infty i}\Phi(\varphi_{Tk})\varphi_{i,k}} = \frac{v_{\infty 1} - \sum_{i=1}^{k} v_{\infty i}\varphi_{i,k}}{v_{\infty 2} - \sum_{i=1}^{k} v_{\infty i}\varphi_{i,k}} \tag{5}$$

When the solids content increases from $\varphi_{i,k}$ to $\varphi'_{i,k}$, Equation 5 is updated to Equation 6:

$$\frac{v'_{1,k}}{v'_{2,k}} = \frac{v_{\infty 1} - \sum_{i=1}^{k} v_{\infty i}\varphi'_{i,k}}{v_{\infty 2} - \sum_{i=1}^{k} v_{\infty i}\varphi'_{i,k}} \tag{6}$$

where $v'_{i,k}$ is the settling velocity of particle species i in zone k when the initial solids concentration is $\varphi'_{i,k}$.

Based on Equations 5 and 6, the relationship $\frac{v'_{1,k}}{v'_{2,k}} < \frac{v_{1,k}}{v_{2,k}}$ can be established when all velocities are positive (indicating downward settling direction). Additionally, an increase in solids content has been found to correspond with a decrease in settling velocity, as supported by the settling time date listed in Table 1. This finding indicates that increasing the solids concentration reduces the relative difference between particle species, thereby decreasing the segregation degree of coarse particles. The comparison between the subplots in Figures 9a and 9f illustrates the suppression of the segregation phenomenon as the solids content increases from 30 to 50%.

It is crucial to note that the discussion presented operates under the assumption that the slip velocity of particle species is a product of the terminal falling velocities and total local solids concentration, disregarding other potential influencing factors. In our study, the suppression of segregation is strongly associated with the degree of aggregation within the suspension, a factor not explicitly integrated into our model derivation. Hence, incorporating more factors or variables into the model might yield a more comprehensive understanding of the observed differential settling behaviour.

4.3.3 Maximum solids content of the particle species in the sediment

The maximum solids content within sediment holds significant engineering implications. Our experimental findings underscore the variation in sediment composition, inherently tied to the settling behaviors exhibited by all particle species within the suspension. The application of the differential settling model provides crucial insights into comprehending the sediment formation. If we disregard compression settling (self-weight consolidation), the settling velocity of particles in the sediment tends toward zero. Consequently, Equation 4 for zone m at the bottom of the suspension can be reformulated as Equation 7:

$$\varphi_{i,M} = \frac{(U_M - v_{i,m})\varphi_{i,m}}{U_M} = \varphi_{i,m}(1 + \frac{v_{i,m}}{-U_M}) \tag{7}$$

As previously demonstrated, the difference between $v_{i,m}$ values diminishes with increasing local solids content. For particles within the same settling zone, they share the same U_M. Consequently, the difference in maximum $\varphi_{i,M}$ between particle species should also decrease. When comparing the maximum solids content of all six species at the bottom, it's evident that the difference in solids content between different particle species decreases as the solids content increases, which aligns with our model analysis.

For a specific suspension, the variables contained in Equation 7 vary when the sediment encounters different zones. Consequently, the maximum solids content of each particle species varies at different heights. It doesn't have to follow a monotonic changing pattern. Take Figure 9c as an example, the solids contents of the A and B species are relatively uniform along the vertical direction. However, a concentration of the D and E species can be clearly observed at the height of 8 cm. Additionally, this accumulation behaviour also varies when the initial solids content of the suspension is different. In Figure 9e where the solids content is increased to 50%, the concentration of the particle species D is not observed.

It's crucial to emphasise that while Equation 7 provides a mathematical tool for calculation, the maximum solids content is not essentially determined by these variables but is influenced by the packing pattern of particles, which, in our context, is primarily affected by the material's PSD and particle shape. According to the experimental findings, the total maximum solids content of the sediment varies with height. As the height increases from the bottom of the column, the proportion of coarse particles decreases due to segregation, resulting in a less well-graded PSD and an increased void ratio. Consequently, this leads to a decrease in local solids content. Unfortunately, the variability of the maximum solids content of the sediment is not well addressed in the zone-formation settling model.

5 Conclusion and recommendation

The experimental and theoretical investigation of the copper tailings suspension has provided significant insights into the differential settling behaviour of the particles. Notably, hindered settling has been observed within specific initial solids content ranges of 30 to 50%. Examination of the PSD results revealed that differential settling primarily occurred among larger particle species. Interestingly, following the segregation of large particles, no settling zone – as indicated by the zone differential settling mode– was observed within the hindered settling region for fine particles. These findings underscore the necessity for a prudent classification or pre-assessment of particle species when utilizing the zone-formation differential settling method, suggesting the potential grouping of fine particles exhibiting similar settling velocities into a single species to simplify the analysis.

The variation observed in segregation degree across different initial solids content levels can be explained through an examination of the existing settling velocity model. This model demonstrates a reduction in relative differences in settling velocities among particle species as the initial solids content increases. However, it is conceivable that a more intricate relationship might underpin this phenomenon if additional influential factors are incorporated into the analysis. While Equation 7 provides a mathematical lens to comprehend the formation of the sediment by analysing the particle settling velocity and the upward propagation of the sediment boundary, it fails to explain the variance in maximum solids content across different sediment heights. This variability appears to be influenced by particle packing patterns governed by

PSD and particle shape. The experimental findings, notably from interruptive settling tests, emphasise the necessity for a more comprehensive settling model that incorporates detailed aspects of particle packing and PSD characteristics.

Additionally, it should be emphasised that the wall effect, a factor overlooked in Kynch theory, is not explored in our study. The diameter of the settling column could potentially influence the experimental results of the settling velocity and the overall behaviour, requiring thorough investigation in future studies. The sampling method employed in this study necessitates the sample collection process to be completed within a relatively short time, as the settling process continues during sample collection.

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