Advanced Continuous-Monitoring Column Test for Sedimentation Analysis of Mine Drainage Sludge

Dong-Kil Lee[1], Youngwook Cheong[1], Sangwoo Ji1, Giljae Yim[1]

[1]Korea Institute Geoscience and Mineral Resources (KIGAM), 124 Gwahang-no, Yuseong-gu, Daejeon 34132, South Korea, corresponding author's phone number: +82-42-868-3228, e-mail address: ldk@kigam.re.kr, ORCID 0000-0003-3121-6405

Abstract

Understanding the settling behavior of mine drainage sludge is critical for enhancing the performance and reliability of sedimentation systems used in acid mine drainage (AMD) treatment. Traditional settling column tests depend on discontinuous sampling, which limits their ability to capture real-time concentration changes, accurately define the hindered settling zone, and evaluate depth-specific removal efficiency. These limitations restrict effective settling pond design and hinder prediction of sludge movement and accumulation. This study introduces a column monitoring system that integrates ten turbidity sensors with periodic photometric TSS calibration to continuously measure concentration variations along a 2-m column. By converting turbidity signals into accurate TSS values and constructing a temporal–spatial TSS distribution map, the method enables high-resolution observation of sedimentation dynamics that cannot be achieved with conventional batch sampling techniques. The proposed system clearly identifies the hindered settling region as the zone where TSS remains constant over time and visualizes the downward progression of the precipitate interface. Results show that complete removal at any depth occurs only when the interface passes that location, with the highest settling velocity and removal efficiency observed between 0.4 and 1.4 m below the water surface. The maximum overflow rate achieving 100% removal occurs near 1.2 m depth, corresponding to the region of most rapid interface descent. The continuous-monitoring approach greatly improves the ability to evaluate sedimentation behavior and provides a more accurate framework for optimizing settling pond design, overflow rate selection, and sludge management strategies. Its applicability extends beyond mine drainage treatment to water purification, wastewater engineering, and industrial processes where real-time assessment of settling performance is essential.

Keywords: Mine drainage, sedimentation, column settling test, total suspended solids, hindered settling

Introduction

Sedimentation of neutralization sludge is a key unit process in acid mine drainage (AMD) treatment because it controls clarified-water quality, sludge inventory, and downstream handling. Active neutralization using lime or caustic soda produces metal-rich hydroxide precipitates that must be separated in settling ponds or clarifiers (Brown *et al.* 2002; Akcil and Koldas 2006; Wolkersdorfer 2023). Therefore, the assumed surface overflow rate (SOR) and the dominant settling regime directly affect treatment reliability and pond sizing (U.S. Environmental Protection Agency 2023).

Related studies show the need for depth-resolved observation. The settling column test was first developed to determine slime-settling tank capacity (Coe and Clevenger 1916) and is still used for sludge and wastewater solids. Recent international work has improved column-test interpretation through sludge densification experiments (Roche *et al.* 2022), while turbidity-based monitoring has been used as a practical proxy for suspended solids, although the turbidity-TSS relationship depends on particle properties and site conditions (Gao 2006). In South Korea, Lee *et al.* (2023)

characterized depth-dependent properties of mine drainage sediments in settling ponds, and Lee *et al.* (2025) demonstrated that sensor-based column monitoring can reveal temporal and spatial TSS distributions. These studies indicate that continuous, depth-resolved monitoring can provide information that conventional intermittent sampling cannot capture.

Conventional settling column tests typically rely on intermittent sampling at a limited number of depths. Such batch-style sampling can miss rapid concentration changes, obscure the spatial extent of the hindered-settling zone, and complicate the derivation of depth-specific removal and overflow criteria. These limitations become more severe for flocculent mine drainage sludge, where the turbidity-TSS relationship may drift during settling because particle size distribution, floc structure, and optical properties evolve.

Here we introduce an advanced, continuous-monitoring column test that integrates multi-depth turbidity sensing with periodic TSS calibration, enabling reconstruction of a spatiotemporal TSS distribution map. Using this map, we (i) identify the hindered-settling region consistently, (ii) quantify interface dynamics, and (iii) compute depth-specific maximum SOR values for complete (100%) removal as a design linkage to full-scale settling ponds.

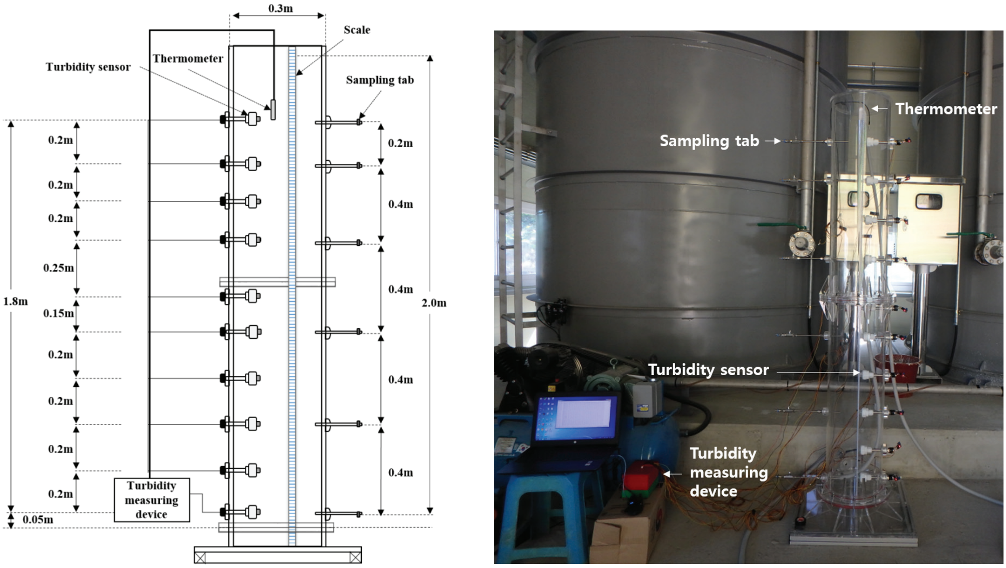
Methods

Instrumentation and data logging

Ten low-cost turbidity sensors (DFRobot Gravity analog turbidity sensor, SEN0189) were used as optical proxies for suspended solids (DFRobot, accessed 2026-03-11). Sensor signals were recorded as analog voltage at 1 Hz using a multi-channel data-logging unit (Arduino Mega class) with an RTC and microSD storage. To reduce high-frequency noise, 1-Hz measurements were aggregated to 1-min means for analysis.

Settling column configuration

A transparent acrylic column (2.0 m water depth) was equipped with ten turbidity sensors and matching sampling taps installed at the same elevations (Fig. 1). A scale and thermometer were placed to visually track the precipitate interface and temperature. The column was filled to 2.0 m with mine drainage sludge generated by AMD neutralization.



(a) Schematic diagram

(b) Photo of the equipment

Figure 1 *Column experimental equipment.*

TSS measurement and calibration strategy

Grab samples were collected from all sampling taps every 10 minutes and analyzed for TSS using a Hach DR900 spectrophotometer following the photometric suspended-solids method at 810 nm (Hach Company 2015). Each sample was gently homogenized, transferred to a clean cell, and measured after blank correction. These periodic TSS values were used to calibrate and verify the voltage-TSS relationship at each sensor over time, enabling conversion of continuous voltage traces into quantitative TSS profiles. A preliminary response check using a coffee solution with known TSS levels (Fig. 2) was also performed to assess inter-sensor variability and sensitivity loss at high concentrations.

Spatiotemporal reconstruction and design linkage

Converted TSS profiles were interpolated in the vertical direction to obtain a continuous spatiotemporal TSS field (Fig. 3). Depth-specific removal was evaluated as a function of detention time, and the maximum SOR achieving 100% removal at each depth was derived (Fig. 4) as an actionable design/operation criterion for settling ponds.

Results and Discussions

Spatiotemporal settling behavior

The reconstructed TSS field shows that the upper and middle water column maintained quasi-constant TSS during the early stage and then declined rapidly when the precipitate interface passed each elevation. This pattern indicates collective settling of flocculent particles rather than independent discrete-particle settling. Near the bottom, TSS increased with time because solids accumulated and were compressed under the overlying precipitate. These opposite trends demonstrate the transition from hindered settling to transition/compression settling and show why continuous sensing resolves sedimentation dynamics that batch sampling can obscure.

Identification of the hindered-settling zone

In the TSS map (Fig. 3), the hindered-settling region is delineated as the zone where TSS remains approximately time-invariant and close to the initial suspension concentration. This interpretation is consistent with the concept that TSS remains nearly constant in the hindered-settling phase (DallaValle *et al.* 1958; Metcalf and Eddy *et al.* 2003). The downward migration and gradual narrowing of this constant-TSS zone show that the floc

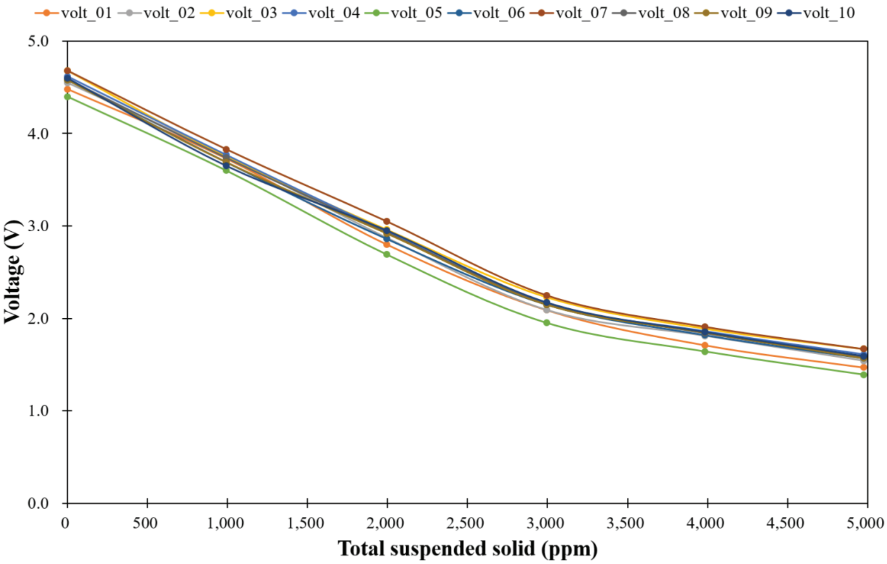


***Figure 2** Variation of voltage for each turbidity sensor according to TSS using solid coffee.*

network initially settles rapidly as a bulk suspension, but the available settling space decreases as the sludge blanket grows upward. Consequently, the highest settling velocity and removal efficiency occur between 0.4 and 1.4 m below the water surface.

Depth-specific overflow-rate criterion (SOR)

From the depth-resolved removal trajectories, the maximum SOR achieving 100% removal was computed for each depth (Fig. 4). Complete removal occurred only after the precipitate interface passed the relevant depth, confirming that clarification is controlled by interface descent rather than by local dilution alone. Values exceeded approximately 30 m^3 d^{-1} m^{-2} between 0.4 and 1.4 m below the surface, with a peak near 1.2 m depth. The lower SOR near the top reflects the initially diffuse interface, whereas the decrease at greater depth reflects sludge-blanket growth and compression. Thus, the optimum design interval is where the interface moves most rapidly before compression becomes dominant.

Conclusions

A continuous-monitoring settling column test was developed by integrating ten multi-depth turbidity sensors with periodic photometric TSS calibration. The method reconstructs a spatiotemporal TSS field that clarifies settling-regime transitions, identifies

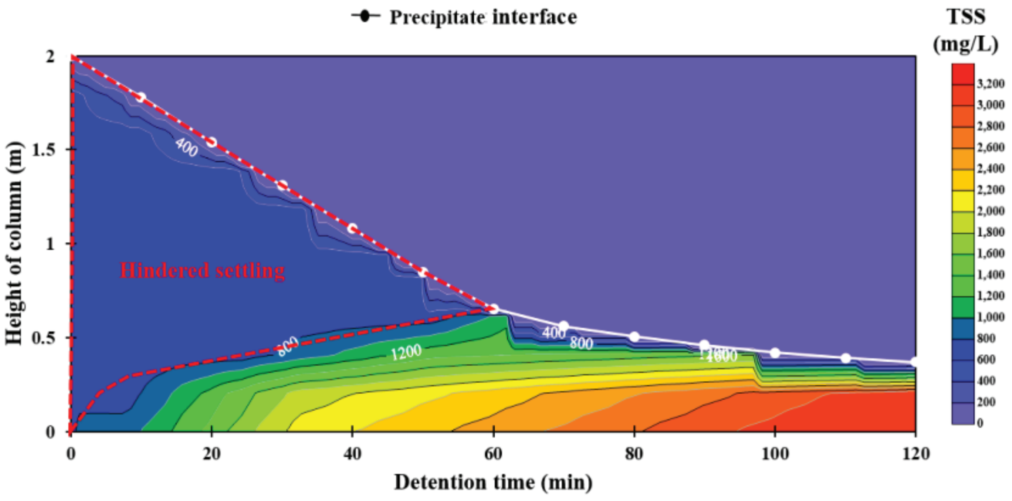


Figure 3 *TSS distribution of precipitate over time in the column.*

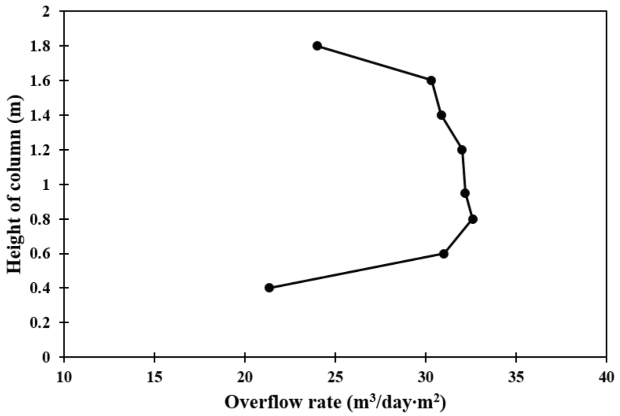


Figure 4 *Maximum overflow rate for 100% overall percent removal by column height.*

the hindered-settling region, and enables computation of depth-specific maximum SOR values for 100% removal.

For the studied mine drainage sludge, the most effective settling zone occurred between 0.4 and 1.4 m below the water surface, and the maximum SOR for complete removal peaked near 1.2 m depth. Future work should focus on standardized QA/QC, sensor-fouling mitigation, and pilot/full-scale validation.

Acknowledgements

This research was supported by the Basic Research Program of the Korea Institute of Geoscience and Mineral Resources (KIGAM), funded by the Ministry of Science and ICT, Republic of Korea.

References

Akcil A, Koldas S (2006) Acid mine drainage (AMD): causes, treatment and case studies. Journal of Cleaner Production 14(12-13):1139-1145.

Brown M, Barley B, Wood H (2002) Minewater Treatment: Technology, Application and Policy. IWA Publishing, London.

Coe HS, Clevenger GH (1916) Methods for determining the capacities of slime-settling tanks. Transactions of the American Institute of Mining Engineers 55:356-385.

DallaValle JM, McBride JP, Allred VD, Jones EV (1958) Application of hindered settling to particle size measurement. Oak Ridge National Laboratory, Tennessee.

DFRobot (accessed 2026-03-11) Gravity: Analog Turbidity Sensor for Arduino, SKU SEN0189, specifications and documentation.

Gao Q (2006) Correlation of total suspended solids (TSS) and suspended sediment concentration (SSC) test methods. New Jersey Department of Environmental Protection, Division of Science, Research, and Technology.

Hach Company (2015) Suspended Solids, Photometric Method 8006, DOC316.53.01139.

Lee DK, Lee JH, Cheong YW, Park JM (2023) Physical properties of mine drainage sediment according to depth in settling ponds. International Journal of Mining, Reclamation and Environment 37(2):148-161.

Lee DK, Cheong YW, Ji S, Yim G (2025) Evaluation of concentration distribution and settling efficiency of mine drainage precipitate through a new column settling experiment. Mine Water and the Environment 44:765-776.

Metcalf, Eddy, Tchobanoglous G, Stensel H, Ryujiro T (2003) Wastewater Engineering: Treatment and Reuse, 4th edn. McGraw-Hill, Boston.

Roche C, Medina MEV, Schmitt P, Pallarès A, Pallarès G, Meilliez M, Laurent J (2022) Densification of activated sludge for better settling performances: experimental characterization in batch column and model parameters calibration. Water Science and Technology 86(1):110-127.

U.S. Environmental Protection Agency (2023) Primary Clarifiers for Operators. EPA Operator Webinar Series slides, August 24, 2023.

Wolkersdorfer C (2023) Mine Water Treatment: Active and Passive Methods. Springer.