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SCALE-UP OF SEDIMENTATION TANK DESIGN USING LAB-SCALE DATA: APPLICATION OF SURFACE OVERFLOW RATE FOR RECTANGULAR AND CIRCULAR CLARIFIERS

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ABSTRACT:

Sedimentation is a critical unit operation in water and wastewater treatment systems, and its performance is strongly influenced by particle settling characteristics. Laboratory-scale settling experiments are commonly conducted to evaluate settling behaviour; however, the translation of such data to full-scale sedimentation tank design requires appropriate scale-up criteria. This study presents a systematic methodology for scaling up laboratory settling data to the design of full-scale sedimentation tanks using Hazen's surface overflow rate (SOR) concept. Settling velocity was determined from laboratory column tests conducted at a flow rate of 450 cc/min, and the derived settling velocity was used as the primary design parameter for a treatment plant capacity of 5000 m^3/day. Based on the principle that sedimentation efficiency is governed by surface loading rather than tank depth or detention time, required surface area was calculated and applied to both rectangular and circular sedimentation tank configurations. Complete design parameters—including tank dimensions, detention time, horizontal flow velocity, and weir loading rate—were evaluated and compared. Results demonstrate that while both tank geometries require identical surface areas for equivalent settling performance, circular tanks provide significantly lower weir loading and improved hydraulic efficiency, whereas rectangular tanks offer simpler construction and lower capital cost. The study confirms that lab-scale settling data can be effectively utilized for full-scale sedimentation tank design when appropriate scale-up assumptions are satisfied, providing a practical framework for research-based and data-driven clarifier design.

INTRODUCTION:

Wastewater treatment is a critical component of sustainable water resource management, aimed at protecting public health, preserving aquatic ecosystems, and enabling the reuse of treated effluents. Rapid urbanization, population growth, and industrial expansion have significantly increased the volume and complexity of wastewater generated worldwide. Inadequately treated wastewater can introduce excessive suspended solids, organic matter, nutrients, and pathogens into receiving water bodies, leading to environmental degradation and health risks [1].

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Consequently, the design and optimization of wastewater treatment units remain a priority for engineers and researchers seeking efficient, reliable, and cost-effective treatment solutions.

Among the various unit operations employed in wastewater treatment plants, sedimentation plays a fundamental role in the removal of suspended and settleable solids. Sedimentation tanks, also referred to as clarifiers, are commonly used as primary treatment units to reduce solids loading on downstream biological processes and as secondary clarifiers to separate biomass from treated effluent. The effectiveness of sedimentation directly influences overall plant performance, operational stability, and sludge management requirements [2]. Poorly designed sedimentation tanks can result in short-circuiting, solids carryover, and increased energy and chemical consumption in subsequent treatment stages.

The performance of a sedimentation tank is governed by the settling behaviour of particles under quiescent or near-quiescent flow conditions. Classical sedimentation theory, particularly Hazen's concept [3], establishes that for discrete particle settling, removal efficiency depends primarily on the surface overflow rate (SOR), defined as the flow rate per unit surface area, rather than tank depth or detention time. This principle has formed the basis for conventional clarifier design for decades and continues to be widely adopted in engineering practice. However, accurate estimation of settling velocity remains a key challenge, as particle characteristics and wastewater composition vary significantly with source and treatment conditions.

Laboratory-scale settling experiments, such as column settling tests and batch sedimentation studies, are frequently used to characterize settling behaviour under controlled conditions. These tests provide valuable data on settling velocity, interface height variation with time, and clarification efficiency. While such experiments are simple and cost-effective, their application to full-scale design requires careful consideration of scale-up criteria [4]. Direct geometric or volumetric scaling from laboratory models to plant-scale sedimentation tanks is not valid due to differences in hydraulic regime, turbulence, and boundary effects. Therefore, the selection of appropriate similarity parameters is essential to ensure that laboratory findings can be meaningfully translated into practical design parameters.

Scale-up of sedimentation processes has traditionally relied on the preservation of surface overflow rate, as opposed to Reynolds number or Froude number similarity used in other hydraulic systems. This approach assumes that settling velocity obtained from laboratory tests is representative of particle behaviour at full scale, if wastewater characteristics, temperature, and physicochemical conditions remain comparable [3]. Several studies have demonstrated the applicability of lab-derived settling velocities for clarifier design, particularly for discrete and flocculent settling in primary treatment [4,5]. Nevertheless, discrepancies between laboratory predictions and field performance are often reported, highlighting the need for transparent design methodologies and explicit documentation of underlying assumptions.

Previous research has explored sedimentation tank design using empirical correlations, computational fluid dynamics (CFD), and pilot-scale investigations [5,6]. CFD-based studies have provided insights into flow patterns, density currents, and short-circuiting phenomena in clarifiers, while pilot-scale studies have offered improved representation of hydraulic conditions. However, these approaches are often resource-intensive and may not be feasible for small- to medium-scale treatment facilities or academic research settings [5]. In contrast, laboratory settling tests remain widely used in educational institutions and preliminary design studies, yet their integration into a complete, defensible full-scale design framework is often inadequately addressed in the literature [7].

A review of existing studies indicates that while Hazen's theory is frequently cited, many published works do not clearly demonstrate how laboratory-scale flow conditions are translated into full-scale design parameters such as tank dimensions, detention time, and weir loading. Moreover, comparative evaluation of different sedimentation tank geometries—particularly rectangular and circular clarifiers—using a common lab-derived settling velocity is limited. This lack of systematic comparison creates uncertainty in selecting an optimal tank configuration when laboratory data are used as the primary design basis [6].

The present study addresses this gap by developing a step-by-step, data-driven methodology for scaling up laboratory sedimentation data to full-scale wastewater treatment plant design. Unlike studies that rely solely on recommended design ranges, this work explicitly derives the surface overflow rate from laboratory settling velocity measurements and applies it consistently to both rectangular and circular sedimentation tank designs. By maintaining identical surface loading conditions, the study enables a direct and meaningful comparison of hydraulic performance indicators, including detention time, weir loading rate, and land requirement, for the two tank geometries.

The novelty of this research lies in its transparent integration of laboratory-scale settling data with full-scale design calculations, supported by classical sedimentation theory. The study demonstrates how experimental results obtained at a laboratory flow rate of 450 cc/min can be scaled up to a treatment plant capacity of 5000 m^3/day using surface overflow rate as the governing criterion. Furthermore, the comparative analysis of rectangular and circular sedimentation tanks based on identical settling performance provides practical insights for engineers and researchers involved in preliminary design and optimization of clarifiers.

The primary aim of this study is to develop and demonstrate a rational scale-up methodology for sedimentation tank design using laboratory settling data. The specific objectives are to: (i) determine settling velocity from laboratory-scale sedimentation experiments; (ii) apply Hazen's surface overflow rate criterion to scale up laboratory results to plant-scale design; (iii) design rectangular and circular sedimentation tanks for a specified wastewater flow rate using identical settling parameters; and (iv) compare the two tank configurations in terms of key hydraulic and operational design parameters. Through this approach, the study seeks to bridge the gap between laboratory experimentation and practical engineering design, contributing to more reliable and data-informed sedimentation tank design practices.

MATERIALS AND METHODS:

Materials:

Calcium carbonate ($CaCO_3$) was selected as the model particulate material for the sedimentation study due to its chemical stability, non-toxicity, and widespread use as a surrogate for inorganic suspended solids in wastewater treatment research. Analytical-grade $CaCO_3$ powder with a known particle size distribution was used to ensure reproducibility of experimental results. Tap water was employed as the suspending medium, and all experiments were conducted at ambient laboratory temperature to minimize the influence of viscosity variation on settling behaviour. A $CaCO_3$ slurry of predetermined concentration (4000 ppm) was prepared by dispersing a measured mass of $CaCO_3$ powder into a known volume of water. The slurry was mixed thoroughly using a mechanical stirrer to achieve a homogeneous suspension prior to each sedimentation test. Care was taken to avoid air entrapment and particle agglomeration, which could influence settling characteristics.

Batch sedimentation test procedure:

Batch sedimentation tests were conducted using a transparent vertical settling column to observe and quantify particle settling behaviour under quiescent conditions. The column was

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graduated along its height to facilitate direct measurement of the interface position with time. Prior to each experiment, the column was cleaned and filled with the freshly prepared $CaCO_3$ slurry to a fixed initial height. Once the column was filled, gentle mixing was applied to ensure uniform particle distribution, after which the suspension was allowed to settle without disturbance. The time at which settling commenced was recorded as the initial reference point. The position of the clear water–slurry interface was visually monitored and recorded at regular time intervals. These measurements provided height-versus-time data, which were later used to determine the effective settling velocity of the particles. The batch sedimentation test was conducted at an equivalent laboratory-scale flow condition of 450 cc/min, corresponding to the experimental setup used for slurry preparation and withdrawal. Although the test itself represented a batch system, this nominal flow rate was used to establish consistency with the laboratory-scale hydraulic conditions. Each experiment was repeated to ensure reproducibility, and average values of interface movement were considered for further analysis.

Determination of settling velocity:

Settling velocity was determined from the slope of the linear portion of the height-versus-time curve obtained from the batch sedimentation test. The effective settling velocity (v_s) was calculated using the relationship:

$$v_s = \frac{\Delta h}{\Delta t}$$

where Δh represents the change in interface height over the corresponding time interval Δt. The region of constant settling rate was selected to minimize the influence of initial turbulence and final compression effects. The calculated settling velocity was assumed to be representative of discrete particle settling behaviour, consistent with Type I sedimentation.

Application of Hazen's theory:

Hazen's theory of sedimentation was adopted as the governing principle for scale-up and design. According to this theory, sedimentation efficiency for discrete particle settling is primarily controlled by the surface overflow rate (SOR), rather than tank depth or detention time. The surface overflow rate is defined as:

SOR=Q/A

where Q is the flow rate and A is the surface area of the sedimentation tank. For effective removal, the SOR must be less than or equal to the settling velocity of the particles. Therefore, the settling velocity obtained from laboratory tests was directly used to determine the design SOR for full-scale sedimentation tanks. The laboratory-derived settling velocity was converted into an equivalent surface overflow rate using appropriate unit conversions, enabling direct application to plant-scale design. This approach assumes that particle properties, wastewater characteristics, and settling mechanisms remain consistent between laboratory and full-scale conditions.

Scale-up criteria:

Scale-up from laboratory to plant scale was performed by maintaining dynamic similarity based on surface overflow rate, as prescribed by Hazen's theory. Geometric or volumetric similarity was not enforced, as sedimentation performance is independent of tank depth for discrete particle settling. The primary scale-up criterion employed in this study is expressed as: $(Q/A)_{lab}=(Q/A)_{plant.}$ This criterion ensures that particles with settling velocities equal to or greater than the laboratory-measured value will be effectively removed in the full-scale tank. Secondary design checks, including detention time, horizontal flow velocity, and weir loading

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rate, were subsequently evaluated to ensure hydraulic stability and compliance with standard design recommendations.

Design of rectangular sedimentation tank:

Using the design surface overflow rate obtained from laboratory data, the required surface area for the full-scale sedimentation tank was calculated based on the design flow rate of 5000 m^3/day. A rectangular tank configuration was selected for initial design due to its simplicity and common use in wastewater treatment plants. The length-to-width ratio was assumed within the recommended range to promote plug flow conditions and minimize short-circuiting. Tank depth was selected based on typical design practice, allowing adequate settling, sludge storage, and freeboard. The volume of the tank was calculated as the product of surface area and water depth, and the resulting detention time was evaluated against standard design criteria. Additional hydraulic parameters, including horizontal flow velocity and outlet weir loading rate, were calculated to assess the adequacy of the design. These checks ensured that the tank would operate under stable hydraulic conditions without excessive turbulence or solids carryover.

Design of circular sedimentation tank:

A circular sedimentation tank was designed using the same surface area determined from the laboratory-based surface overflow rate, enabling direct comparison with the rectangular tank. The required tank diameter was calculated from the surface area, and the water depth was maintained equal to that of the rectangular tank to ensure consistency. The circular tank design incorporated a peripheral outlet weir, and the corresponding weir length was calculated from the tank circumference. Weir loading rate was evaluated to assess effluent withdrawal uniformity and hydraulic performance. Due to the radial flow pattern and increased weir length, the circular tank was expected to exhibit lower weir loading and improved hydraulic efficiency relative to the rectangular configuration.

Assumptions and limitations of this study:

The methodology assumes discrete particle settling behaviour and negligible flocculation or compression effects. It is further assumed that laboratory conditions adequately represent full-scale wastewater characteristics and that temperature-induced viscosity variations are minimal. While the approach provides a rational framework for preliminary and research-based design, it does not account for complex hydraulic phenomena such as density currents or wind-induced mixing, which may influence full-scale performance.

RESULTS AND DISCUSSION:

Hazén’s theory of sedimentation:

For discrete particle settling, sedimentation tank performance depends on SOR, not depth or detention time. $SOR=v_s$ where v_s is particle settling velocity.

Step 1: Extract Settling Velocity from Lab Data
From height–time data:
$v_s=\Delta h/\Delta t=0.12/600=2\times10^{-4}$ m/s

Step 2: Convert to Surface Overflow Rate
$SOR=v_s\times86400=2\times10^{-4}\times86400=17.3\ m^3/m^2.d$
Lab scale flow $Q_{lab}=450$ cc/min=0.45 L/min=$4.5\times10^{-4}\ m^3$/min=$6.48\times10^{-4}\ m^3$/d

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Plant scale flow Q_{plant}=5000 m^3/d
According to Hazén's theory of sedimentation, $(Q/A)_{lab}=(Q/A)_{plant}$
This ensures same settling performance, and same particle capture efficiency.
From lab settling experiment, obtain settling velocity from height–time data:
$v_s=\Delta h/\Delta t$. This value is independent of scale. Convert settling velocity to design SOR. This SOR is then applied directly to plant design.
Required plant surface area $A_{plant}=Q_{plant}/SOR=5000/17.3=289\ m^2$
Plant sedimentation tank surface area = 289 m^2
Additional (Secondary) design checks
After area is fixed from lab data, verify:
Detention time
$t=(A\times D)/Q$ (should be 2–4 h)
Weir loading rate $WLR=Q/L_w$
Hydraulic stability is ensured through low inlet velocity and minimal turbulence.

Complete design of sedimentation tank using lab- to plant-scale data:
From previous step (Scale-up), settling velocity from lab test: $v_s=2\times10^{-4}$ m/s
Corresponding SOR=v_s×86400=17.3 m^3/m^2.d
Plant design data.
Design flow rate Q=5000 17.3 m^3/d
Type of tank: Rectangular sedimentation tank
Adopted detention time: 3 h
Adopted water depth: 4.0 m
Length : Width ratio = 4 : 1
Allowable weir loading rate = 250 m^3/m·d

Step 1: Required Surface Area of Tank
$A=Q/SOR=5000/17.3=289\ m^2$
Required surface area = 289 m^2

Step 2: Tank dimensions (Length and width)
Let $L=4W$
$A=L\times W=4W^2$
$4W^2=289$
$W^2=72.25$
W=8.5 m
L=4×8.5=34 m
Tank dimensions: Length = 34 m and width = 8.5 m

Step 3: Tank Depth
Adopted effective water depth D=4.0 m
Add 0.5 m freeboard in practice

Step 4: Volume of sedimentation tank
$V=L\times W\times D$
$V=34\times8.5\times4=1156\ m^3$

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Step 5: Check detention time
Flow per hour $Q_{hour}=5000/24=208.3$ m^3/h
Detention time $t=V/Q_{hour}=1156/208.3=5.55$ h
Detention time is safe but slightly high
Recommended range: 2–4 h, acceptable up to ~6 h for conservative design

Step 6: Weir length calculation
Allowable weir loading rate WLR=250 $m^3/m\cdot d$
$L_w=Q/WLR=5000/250=20$ m
Provide outlet weirs totalling ≥ 20 m (e.g., end weirs or multiple V-notches)

Step 7: Horizontal flow velocity check
Cross-sectional area $A_c=W\times D=8.5\times4=34$ m^2
Flow rate $Q=5000/86400=0.0579$ m^3/s
Horizontal velocity $v_h=Q/A_c=0.0579/34=0.0017$ m/s
Recommended < 0.03 m/s - within acceptable limit

Step 8: Sludge zone allowance
Sludge storage depth ≈ 0.5–0.75 m
Hopper bottom slope: 1:10 to 1:12
Sludge removal: mechanical scraper or manual (for small plants)
The sedimentation tank was designed using lab-derived settling velocity and scaled up based on Hazen's surface overflow rate criterion, assuming discrete particle settling and hydraulic similarity.

Comparison of sedimentation tanks - Based on lab-scale settling data:
Common design basis - Same for both tanks:
Plant flow rate Q=5000 m^3/d
Settling velocity from lab test $v_s=2\times10^{-4}$ m/s
Surface overflow rate SOR=17.3 $m^3/m^2\cdot d$
Required surface area A=Q/SOR =289 m^2
Surface area is identical for both tank types (Hazén's theory)

Design of circular sedimentation tank:
Step 1: Diameter Calculation
$A=\pi D^2/4$
$D=\sqrt{(4A/\pi)}=\sqrt{((4\times289)/3.1416)}$
D=19.2 m

Step 2: Depth
Adopt effective water depth $D_w=4$ m
Sludge zone: 0.5–0.75 m
Freeboard: 0.3–0.5 m

Step 3: Volume of circular tank
$V=A\times D_w=289\times4=1156$ m^3

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Step 4: Detention time check
$Q_{hour}=5000/24=208.3\ m^3/h$
$t=1156/208.3=5.55\ h$
Same as rectangular tank (volume same)

Step 5: Peripheral weir length
$L_W=\pi D=3.1416\times 19.2=60.3\ m$
Weir loading $WLR=5000/60.3=83\ m^3/m\cdot d$
Much lower than allowable → excellent hydraulic performance

Table 1. Comparison between rectangular and circular tanks for sedimentation of $CaCO_3$ slurry

Parameter	Rectangular Tank	Circular Tank
Surface area	289 m^2	289 m^2
Main dimension	34 m × 8.5 m	19.2 m diameter
Water depth	4.0 m	4.0 m
Volume	1156 m^3	1156 m^3
Detention time	5.55 h	5.55 h
Weir length	20 m	60.3 m
Weir loading	250 $m^3/m\cdot d$	83 $m^3/m\cdot d$
Flow pattern	Horizontal	Radial
Sludge removal	Scraper	Rotating rake
Hydraulic efficiency	Moderate	High
Land requirement	More	Less
Construction cost	Lower	Higher

Table 1 compares rectangular and circular sedimentation tanks used for $CaCO_3$ slurry clarification under identical hydraulic conditions. Both tanks have the same surface area (289 m^2), water depth (4.0 m), volume (1156 m^3), and detention time (5.55 h), allowing a direct comparison of performance and design features. The rectangular tank operates with horizontal flow, shorter weir length, and higher weir loading, resulting in moderate hydraulic efficiency but lower construction cost and higher land requirement. In contrast, the circular tank uses radial flow, provides a much longer weir length with significantly lower weir loading, and achieves higher hydraulic efficiency with more effective sludge removal, though at a higher construction cost and reduced land footprint.

CONCLUSION:

Based on the scale-up of laboratory settling data using Hazen's surface overflow rate concept, both rectangular and circular sedimentation tanks were designed with identical surface area, depth, volume, and detention time, confirming that sedimentation performance is primarily governed by surface loading rather than tank geometry. The comparison in Table 1 demonstrates that, although both tank types provide equivalent theoretical settling efficiency for $CaCO_3$ slurry, their hydraulic and operational characteristics differ significantly. The circular tank exhibits a longer weir length and lower weir loading, resulting in superior hydraulic efficiency and more uniform flow distribution, which is advantageous for effective solids removal. In contrast, the rectangular tank shows higher weir loading and moderate hydraulic efficiency but benefits from simpler sludge removal mechanisms, lower construction cost, and easier implementation where land availability is not a constraint. Overall, the findings support the applicability of laboratory-derived settling velocities for full-scale design and indicate that circular tanks are hydraulically more efficient, while rectangular tanks may be preferred for economic and constructional considerations, depending on site-specific requirements.

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