Enhancement of settling tank capacity using a new type of tube settler
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ABSTRACT
The effectiveness of a newly developed lamellar settler was confirmed by onsite experiments. The device had inclined parallel plates arranged in a vertical direction in a settling tank. This vertical arrangement method enables many more plates to be set compared to the conventional horizontal arrangement. As an original and distinctive innovation, both the right and left edges of the plates were closed, for removing the clear water between the plates. The tube settler modules were installed in a final settling tank of a sewage treatment plant. Tests conducted over a 9 months period showed that the system operated successfully and under normal operation conditions, the new device could treat almost the same flow rate as that treated by a conventional tank, 5,000 m³/day. For storm water, the new tube settler was demonstrated to enhance the settling tank capacity by up to 3 times.

Key words | lamellar settler, settling tank, tube settler

INTRODUCTION
Lamellar settlers are widely known to enhance settling tank capacity; they are primarily used in the water purification process. Recently, this technology has been used in other engineering fields, for different purposes such as the segregation of mineral particles (Zhou et al. 2006), improvement of sewage treatment technology (Nurdogan & Oswald 1996; Kolish & Schirmer 2004) and, in particular, enhancement of the capacity for the sewage treatment process (Takayanagi et al. 1997; Bridoux et al. 1998; Daligault et al. 1999; Saleh & Hamoda 1999). Although the conventional lamellar settler system is effective, it has a drawback in that because the parallel plates are arranged horizontally (as shown in Figure 1(A)), the number of plates that can be set in a particular tank is limited by the water surface area of the tank.

The newly developed settler device is an improvement over of the lamella settler, in that it arranges the inclined parallel plates in the vertical direction (See Figure 1(B)). An original and distinctive features of this system is that the right and left edges of the plates are closed to form vertically arranged tubes with a rectangular cross section; this enables the direct removal of separated clear water by suction from the top end of each tube. The objective of this study was to verify the effectiveness of the newly developed tube settlers through onsite experiments.

PRELIMINARY EXPERIMENT

Theory of tube settler

Figure 2 shows a definition sketch of the tube settler where the length, spacing, and angle of inclination are defined by L, d, and θ, respectively. The inflow or suction velocity is U₀ and the settling velocity of the suspended particle is W₀. Since we consider a slow suction velocity and low concentration, an idealized condition is assumed. Thus, the effects of many factors such as the wall shear, turbulence, concentration dependency of settling, and density current on the flow are ignored. The width of the settler is assumed to be of unit length.
Consider the case shown in Figure 2, where the trajectory of the sediment particle is from A to C. From the retention time of the particle, we obtain Equation (1) as follows:

$$\frac{d}{W_0 \cos \theta} = \frac{L}{U_0 - W_0 \sin \theta}$$  \hspace{1cm} (1)

From Equation (1), the flow rate is obtained as follows;

$$U_0 \times d = W_0 (L \cos \theta + d \sin \theta)$$  \hspace{1cm} (2)

The terms in parentheses on the right hand side of the above equation corresponds to the horizontally projected area of the tube settler. Therefore, Equation (2) indicates that the treatment capacity of the device is proportional to its horizontally projected area. Thus, the widely known overflow rate theory is applicable to the case of this tube settler, as reported by Binder & Wiesmann (1983).

According to this theory, the treatment capacity is proportional to the number of plates installed in the settling tank. In general, more plates can be set in the vertical arrangement than the horizontal arrangement. This is, why the high performance can be obtained by the new tube settler system.

**Experiment with tube settler unit**

To determine the precise configuration of the tube settler, many basic investigations were performed through laboratory experiments and by the numerical simulations. In addition, the effects of many factors, such as, the shape and length of a tube settler, suction velocity and sediment concentration of the influent on the performance of the tube settler was carefully examined in a previous study for a practical settling tank (Fujisaki & Terashi 2007). Based on the results from these investigations, the tube settler unit was manufactured and installed into a final settling tank for sewage treatment, as shown in Figure 3. The detailed configuration of the tube settler is shown in Figure 4.

The unit was composed of 8 stainless steel plates are arranged vertically with 0.05m space, the width, length,
and thickness were 0.464 m, 0.7 m, and 2 mm, respectively, while the angle of inclination was set to 60°. In addition both the right and left sides of the plate were closed (See Figure 4). The suspension was sucked into the tube from the lower end and flowed upwards. The cleared water was discharged from the topmost end, while the settled sediments slide down along the bottom side plate.

Using the tube settler unit, the relationship between the suction velocity $U_0$ and the concentration for the suspended sediment of the effluent, $C_{out}$ was investigated. In this experiment, the tube settler unit was suspended near the inlet zone of a settling tank, this was because the vertical variation of concentration is very high in this zone. Thus, we could easily obtain various feed concentrations $C_{in}$ as experimental conditions, by changing the vertical location of the tube settler.

Figures 5 and 6 demonstrate the relationship between $C_{out}$ and $U_0$. The parameter shown in these figures is the sediment concentration of the influent $C_{in}$. The two figures show the results obtained for high and low concentrations respectively. In both cases, $C_{out}$ increased with $U_0$, this tendency became apparent with an increase in the sediment concentration of the feed. In practical operations, to maintain a given water quality for the effluent, we must control the suction velocity $U_0$ corresponding to various feed concentrations $C_{in}$. Thus, the experimental results given in Figures 5 and 6 play a very important role for determining $U_0$.

**Concentration distribution in a settling tank**

Before starting the onsite experiments, we needed to determine the setting location and operating conditions of the tube settler. The onsite experiment was performed in a final settling tank of the Shinmachi sewage treatment plant in Kitakyushu City, Japan. The tank has a length, width and depth of 34, 7 and 3.4 m at the downstream end. This tank usually treats 5,000 m$^3$/day. Near the inlet zone of the tank, the water reaches a depth of up to 8 m. The bottom part of this zone is used as a return sludge hopper.

![Figure 4](image4.png) Configuration of tube settler unit.

![Figure 5](image5.png) Relation between suction velocity and sediment concentration of effluent (high concentration case).

![Figure 6](image6.png) Relation between suction velocity and sediment concentration of effluent (low concentration case).
As a first step of the preliminary work, the concentration distribution of this tank was measured. The numerical values shown in Figure 7 are the concentrations of activated sludge (1 mg/L = \(10^{-3}\) kg/m³). These values were measured when the tank load was tripled to a flow rate of 15,000 m³/day. Therefore, in normal operations, the sludge concentration is lower than these values shown in Figure 7. In Figure 7, the slant line zone indicates the location where the tube settlers were installed. Considering the concentration profile in the tank, as given in Figure 7 and the other experimental results shown in Figures 5 and 6, the suction velocity of the tube settler was set at 0.005 m/s, as a standard. Since the onsite experiment was conducted under normal operating conditions for the treatment site, keeping the quality level of the effluent was the highest priority. Therefore we were requested to set sufficient safe experimental conditions.

### ON-SITE EXPERIMENT

#### Installation of tube settler

When we set \(U_0 = 0.005\) m/s, the treatment capacity of the tube settler unit shown in Figure 3 was \(0.005 \times 0.46 \times 0.05 \times 7 = 8.05 \times 10^{-4}\) m³/s = 69.5 m³/day. To use this tube settler unit, if we treated 5,000 m³/d, we would need approximately 80 tube settler units.

To install 80 units into the settling tank, tube settler modules were prepared. As shown in Figure 8, a module is composed of 8 tube settler units and a trough for the effluent. By interconnecting the modules, two lines of tube settler system were installed into the settling tank. Each line had 5 tube settler modules. The plane view of the setting is illustrated in Figure 9. In this figure, A is the overflow trough of the conventional settling tank, and B is the discharge trough for the effluent of tube settler C. The collected effluent of the tube settlers is discharged from the storage tank by siphoning or by pump discharge.

#### Flow rate control

As the second part of the preparatory work, we checked the flow rate control system. To maintain the sediment concentration of the effluent below the previously determined standard value, the suction velocity must be controlled depending on the sediment concentration of the feed. In this system, the flow rate was controlled by changing the difference between the level on the water surface of the settling tank and the level of the discharge nozzle. Figure 10 shows half of the lateral cross section of this device. Each settling tube unit had two discharge nozzles with a diameter of 0.03 m. In case of low flow rate, the discharge velocity was
controlled by changing the level of the discharge trough, in order to decrease the value of \( \Delta h \), as shown in Figure 10(L). On the other hand, when there is high suction velocity, the tube settler must be set at a lower position to increase in the value of \( \Delta h \), as shown in Figure 10(R). The relationship between the head \( \Delta h \) and the discharge velocity \( V \) can be approximated by an equation derived from Bernoulli’s theory, as shown in Figure 11. The accumulated volume flow rate in the discharge trough is plotted against the flow distance in Figure 12.

A linear relationship is obtained, which implies that each module provided an qual volume of suction in this device.

**Results of on-site experiment**

The onsite real-scale operation of this tube settler was conducted from April to December 2006 at the final settling tank of the previously mentioned sewage treatment plant, using the 80 settling tube units, as shown in Figure 9. As a long-term test run, the device was operated continuously for two weeks without any problem. This indicates that the device was very stable and that the deposited sludge discharged continuously by the removal devise.

The results of the conducted experiments are shown in Figure 13, the treated volume flow rate is plotted on the horizontal axis and the value of SS (suspended sediment concentration of effluent) is plotted on the vertical axis. In this figure, ◆ and ▲ indicate the values for the newly installed tube settler (sampled at trough B in Figure 9), and □ indicates those of the conventional settling tank (trough A, in Figure 9). The data denoted by ▲ were obtained using 40 modules and a flow rate of 5,000 m³/day, the results were then converted into those for 80 modules.
The concentration of the suspended sediment, SS for the effluent was less than 10 mg/L in most cases, as shown in Figure 13. Therefore, we can state that the performance of the tube settler is almost the same as that of a conventional settling tank.

However, the sediment concentration of the conventional tank effluent was slightly low; thus implying that the quality of the effluent from the conventional settling tank is better. When the tube settlers were installed, they absorbed the suspension from the lower part of the settling tank. This intake induced the downward flow of the suspension with a relatively high concentration. Therefore, the clear water near the surface easily flowed downstream.

Another experiment was designed to treat the sudden increase in treatment water in the case of a storm. For this purpose, the suspension for treatment was supplied from the surrounding settling tank, so that, the water quality of the influent would not be the same as that during stormy time but the but as that during normal time. This intake induced the downward flow of the suspension with a relatively high concentration. Therefore, the clear water near the surface easily flowed downstream.

The experiments were conducted in the final settling tank of an urban sewage treatment plant without changing the usual operating conditions. Therefore, the effluents in all of the experiments needed to maintain the discharge water quality standard of this treatment plant. Because of this, the scale of the onsite experiment device was designed to be rather small. The additional surface area produced by the tube settlers was around 100 m², which is less than half that of the original settling tank. The effectiveness of the tube settler, however, was adequately confirmed. Furthermore, an increase in the capacity can be easily attained by installing more tube settlers, because the tube settlers, because the tube settler system installed in the settling tank occupied only 3% of the total settling tank volume.

Discussion: evaluation of density effect

Turbidity current in a settling tank

The reason for the success of the experiment was because the sediment concentration in the area where the tube settlers were installed was very low. This characteristic sediment concentration distribution was caused by a turbidity current near the inlet zone. Due to the concentration difference between the influent and water in the tank, the suspension flowed downwards despite their horizontal inflow. The reference velocity of this density current \( U_{dc} \) is given by

\[
U_{dc} = \sqrt{(\rho_s - \rho_f) / \rho_f} \times C \times g \times H
\]  

Substituting the numerical values given in Table 1, we obtain

\[
U_{dc} = \sqrt{(1.04 - 1.0) / 1.0 \times 0.0013 \times 9.8 \times 7.0} = 0.060 \text{ m/s}
\]
Table 1 | Numerical values of physical quantities

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Physical meaning</th>
<th>Numerical value</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>$\rho_s$</td>
<td>Density of suspended particles</td>
<td>1,040</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>Density of water</td>
<td>1,000</td>
<td>kg/m³</td>
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<tr>
<td>$C$</td>
<td>Concentration of suspension of settling tank influent</td>
<td>0.0013</td>
<td>kg/kg</td>
</tr>
<tr>
<td>$H$</td>
<td>Reference height of return sludge zone</td>
<td>7</td>
<td>m</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration of gravity</td>
<td>9.8</td>
<td>m/s²</td>
</tr>
<tr>
<td>$C_0$</td>
<td>Concentration of suspension of tube settler influent</td>
<td>0.0001</td>
<td>kg/kg</td>
</tr>
<tr>
<td>$U_0$</td>
<td>Suction velocity or mean velocity of tube settler</td>
<td>0.005</td>
<td>m/s</td>
</tr>
<tr>
<td>$d$</td>
<td>Space between lamella plates</td>
<td>0.05</td>
<td>m</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity</td>
<td>$10^{-6}$</td>
<td>m²/s</td>
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This value, is roughly 100 times larger than the settling velocity of the sediment and 10 times larger than the feeding velocity in the settling tank. Therefore, the suspension flows downwards and not horizontally, (like a waterfall), as soon as it enters the settling tank. The mixing of the suspension in the bottom zone of the return-sludge hopper catches most of the sediments of the plunged suspension, the suspension of the decreased concentration then returns upwards as an influent of the usual horizontal settling tank. Thus, the return-sludge hopper plays an important role in the removal of the suspended sediments.

As demonstrated in Figures 5 and 6, the sediment concentration of the effluent increases with the sediment concentration of the influent. To investigate this phenomenon, the effect of density is discussed.

When there is a high concentration, if a clear water zone and suspension zone exists in a tube, the suspension zone moves downwards due to the effect of the excess density of the suspension (Acrivos & Herbolzheimer 1979; Doroodchi et al. 2005). As a measure of this density effect, the densimetric Froude number, $F_{dt}$, is given by

$$ F_{dt} = \frac{U_0}{\sqrt{(\rho_s - \rho_f) / \rho_f \times C_0 \times \sin \theta \times d}} $$

The above equation is the ratio of the suction velocity to the reference velocity of the density current. In our experiment, by assuming $C_0 = 100\, \text{mg/L}$ and using the values given in Table 1, we obtained

$$ F_{dt} = \frac{0.005}{\sqrt{(1.04 - 1.0) / 1.0 \times 0.0001 \times 9.8 \times \sin 60 \times 0.05}} = \frac{0.005}{0.0015} = 3.85 $$

The other non-dimensional parameter is also used, it is defined as

$$ \Gamma = \frac{U_c}{U_0} - \frac{(\rho_s - \rho_f) / \rho_f \times C_0 \times \sin \theta \times (d/2)^2 / \nu}{U_0} $$

The above parameter is derived as the ratio of the excess gravity term to the viscous term in the equation of longitudinal motion. Again using the numerical values given in Table 1, we obtain

$$ \Gamma = \frac{U_c}{U_0} = \frac{(1.04 - 1.0) / 1.0 \times 0.0001 \times 9.8 \times \sin 60 \times (0.05/2)^2 / 10^{-6}}{0.005} = \frac{0.021}{0.005} = 4.2 $$

This parameter is particularly useful when the low Reynolds number is low or the longitudinal variation is significantly smaller than the vertical variation, i.e. small spacing and long plates. As given above, the order of the reference velocity of the turbidity current is on the same order as that of the mean flow velocity in the settling tube, even at low concentrations (e.g. 100 mg/L). Therefore, the effect of the turbidity current is not negligible in many cases and at least a rough estimation should be performed for the design and operation of the tube settlers.

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CONCLUSIONS

By installing a newly developed tube settler into a secondary settling tank of a sewage treatment plant, an onsite experiment was performed. The new system employed a vertical arrangement of lamellar plates, instead of the usual horizontal arrangement, to enhance the treatment capacity.

1. After operating the settler for over 9 months, it was confirmed that the system can treat activated sludge suspension at almost the same flow rate as the original settling tank.

2. For over two weeks of continuous operation, the system needed no maintenance during this test run period, thus, the deposited sludge was also automatically discharged.

3. The space occupied by the tube settler device was only 3% of the original setting tank volume, therefore, by installing more tube settlers, further enhancement of the settling tank can be easily attained.

4. With regard to the peak flow problem, the system succeeded in operation with an up to 3 fold increase in the influent through joint operation of the tube settlers and the conventional settling tank.

5. By installing the tube settler, the treatment efficiency of the conventional settling tank was also enhanced, since the induced current by the tube settler’s intake improved the water quality near the water surface.

6. The density current near inlet zone of the settling tank promoted the settling of sediment. One reason why the tube settlers showed high performance was that the device was set at the location where the sediment concentration was lowered by this density current.

7. For low sediment concentrations, the new device can be a very powerful tool for enhancing settling tank capacity, its effect can be estimated using only the usual overflow rate theory. At high concentrations, the turbidity current in the tube settler must be taken into consideration.

Although the experiments were executed in a sewage treatment plant, the results obtained by this study are applicable to any other settling tank since the phenomenon being treated is the settling of sediments due to gravity.

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REFERENCES


