



# Experimental study to evaluate design procedure and proposed improvement measures for clarifier with inclined plates

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## ABSTRACT

The *Standards for Water Works* issued by the Korean government prescribed the insertion of inclined plates in a clarifier to enhance the settling of the suspended solids. In this study, in order to verify the role of the inclined plates, two identical laboratory-scale rectangular clarifiers were constructed and eight inclined plates were inserted into one of the clarifiers and inflow from same source was treated in both the clarifiers. Dye tests revealed that only the front three of the seven slots received the inflow at  $0.57 \text{ m}^3/\text{m}^2\cdot\text{h}$ , which was the highest SOR (surface overflow rate). Three different SORs, with 12 different SS (suspended solid) concentrations at each overflow rate, were fed to both clarifiers. However, the clarifier with the inclined plates failed to show an improved removal rate for the SS. In order to enable the Boycott effect within the slot, it is suggested that each slot created by the inclined plates receives equalized inflow. Moreover, collision of the inflow with the settled sludge at the bottom of the clarifier has to be avoided. These provisions, which can maximize the Boycott effect, should be added to the *Standards for Water Works* endorsed by Korean government.

**Keywords:** Boycott effect, Clarifier, Inclined plates, SOR(surface overflow rate)

## 1. Introduction

Various methods proposed by many researchers have been employed to increase the settling capacity in clarifiers, including using a double-deck clarifier [1]. Similarly, a stack of tubes, installed horizontally in a clarifier, had proved to increase the settling capacity; however, several problems were associated with this method, such as the installation and operation of a system to remove settled solids at each tube. In particular, it had been reported that the removal of the settled solids without causing resuspension of the solids was problematic [2-4].

It was observed that the settling of the solids in an inclined self-contained tube occurred faster than it did in a vertically positioned tube [5]. In order to prove these observations, settling velocities were measured at 14 different slopes. The results demonstrated that the settling velocity was dependent on the degree of slope, i.e., the larger the degree of slope, the faster settling occurred [6]. The authors claimed that a horizontally projected area from the inclined tube played a role in the settling of the solids and provided extra settling area and, therefore, the larger degree of slope contributed to the faster rate of settling [6]. Boycott first observed the faster settling in a sloped self-contained tube in 1926, and the phenomenon is therefore called the Boycott effect.

Subsequently, inclined tubes had been installed in clarifiers, and good settling rates at relatively short retention times [4] had been reported.

In other research, flow-through tubes at slopes of 30°, 35°, 40°, 55°, and 60° were inserted in a clarifier to enhance the settling of the solids from the backwash water. It was reported that the tube angled at 40° had a higher solid settling capacity than had the tube positioned at 60°. Although the tube sloped at 60° provided a larger horizontally projected area, the authors simply presented the results without further explanation [7]. Sloped flow-through tubes were installed in primary and secondary clarifiers in a wastewater treatment plant to verify the increase in the solid removal capacity, but no improvement in the settling rate was observed. However, it was proven that the tubes in the secondary clarifier dampened the effect of high solid loadings [7].

The Boycott effect was clearly illustrated during an experiment when the parallelly installed inclined plates were moved down in an upflow clarifier. The results from this experiment were compared with a mathematical model and it was proven that the Boycott effect was functioning in the inclined plates [8]. From an experimental study, a mathematical model for the Boycott effect in a sloped tube was proposed [9]. After combining the proposed model and the experimental results from Nakamura and Kuroda



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Received May 7, 2015 Accepted August 31, 2015

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[6], the PKN model was presented and computer simulation, based on the PKN model, was carried out [10]. The fluid dynamics pertaining to the Boycott effect was studied in a single slot, created by two inclined plates installed in a flow-through settler [11, 12]. A higher settling rate was observed when chemically precipitated groundwater was treated in a laboratory-scale upflow clarifier with inclined plates. It was concluded that the surface overflow rate (SOR) could be increased by up to 330% in such an instance [13].

By trial and error, the National Swedish Environmental Board had developed the GEWE lamella sedimentation system, which was an upflow clarifier with inclined plates. This system had demonstrated two important factors for a successful operation, namely, that the inflow into each slot, created by the inclined plates, was equalized and that the direction of the inflow did not interfere with the movement of the settled sludge within the slot [14-16]. A pilot plant for this system was installed at a water treatment plant, along with two other systems. The results from the lamella settler showed superior solid removal efficiency, with the effluent turbidity from this system being below 1.0 NTU when the SOR was  $0.83 \text{ m}^3/\text{m}^2\cdot\text{h}$ . The projected area from the inclined plates was included for the calculation of this SOR [17]. A similar clarifier with inclined plates was developed to treat wastewater from a phosphorus mine [18]. A downflow clarifier with inclined plates was developed and an effluent channel was installed on each upper plate to withdraw supernatant [19, 20]. Inclined plates installed within oxidation ditch were claimed to maintain high MLSS mass to induce MLSS settling to accumulate MLSS at the bottom of ditch [21].

Several handbooks [22, 23] and the *Standards for Water Works* issued by the Korean government [24] refer to a clarifier with inclined plates. This kind of clarifier was proposed for use in the primary clarifier in a wastewater treatment plant, because of the high solid concentrations and the fast precipitation characteristics of solids in domestic wastewater [22].

MWH [23] and the *Standards for Water Works* [24] present a design procedure in detail for a clarifier with inclined plates. The inclined plates are inserted into the existing clarifier structure, as process providers show at their web sites [25, 26]. A rectangular clarifier with inclined plates was designed according to the design procedure described by the *Standards for Water Works* [24], and a CFD (computational fluid dynamics) simulation was carried out to verify the effect of the plates. However, this simulation failed to show improvement in the removal of the solids by adding the inclined plates [27].

Although other research has indicated an increase in the solid removal capacity of a clarifier with inclined plates, and the handbooks and the *Standards for Water Works* [24] have presented a design procedure, a simulation of these procedures showed no improvement in the rate of the solids removal of such a clarifier. In order to verify the effect of the inclined plates, experimental studies have to be performed and operational results from clarifiers, both with and without inclined plates, under similar conditions, have to be analyzed. Such analysis could indicate how the problems in the design procedures of the *Standards for Water Works* should be addressed [24], and which correctional measures would be appropriate to create a clarifier with inclined plates that has a high capacity for solids removal.

## 2. Materials and Methods

In this study, two identical rectangular clarifiers were constructed, with eight inclined plates being inserted into one of the clarifiers. As shown in Table 1, the length, width, and the effective depth of each clarifier were 830 mm, 300 mm, and 308 mm, respectively. A horizontal multi-hole diffuser plate, 30 mm wide and 300 mm long, was placed at a depth of 58 mm at the front end of each clarifier to ensure equalized downflow. This plate had two sets of holes that were positioned symmetrically from the center of the plate. Each set comprised seven holes, with diameters of 7, 8, 9, 10, 12, 15, and 16 mm, and the holes were sequentially located from the center, with the largest hole located the farthest from the center. The distance between the center of the plate and the 7 mm hole was 16 mm. The spaces between the centers of the 7 to 8 mm diameter holes, the 8 to 9 mm diameter holes, the 9 to 10 mm diameter holes, the 10 to 12 mm diameter holes, the 12 to 15 mm diameter holes, and the 15 to 16 mm diameter holes were 21, 20, 18, 18, 20, and 24 mm, respectively. The purpose of the arrangement of the holes in the plate was to induce equal vertical flow, since the inflow was provided by a pump at the center of this plate.

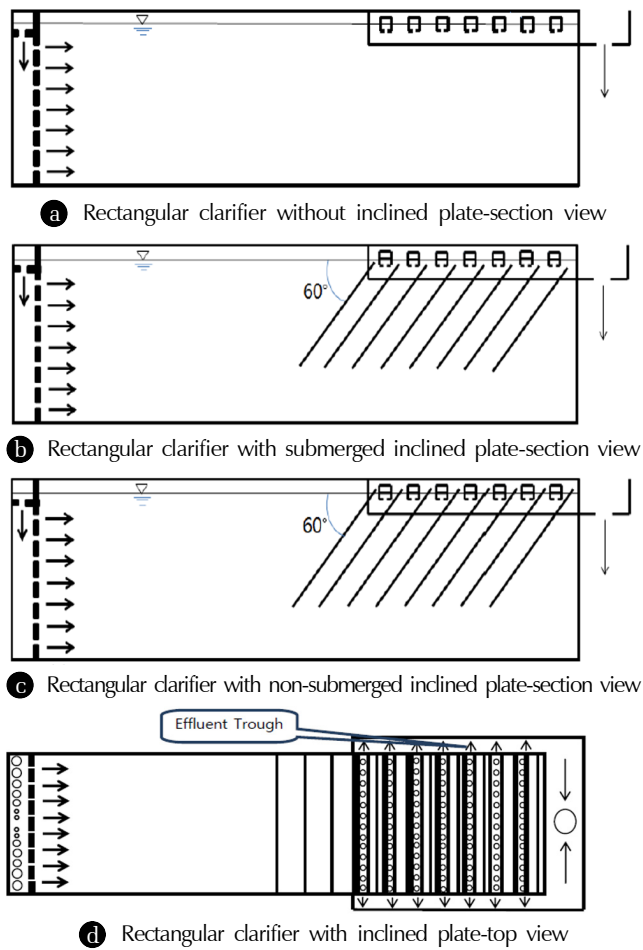
The vertically equalized inflow was introduced to the diffuser panel placed at the front of the clarifier. The role of this diffuser panel was to provide equalized horizontal flow the clarifier. The diffuser panel had 6% of opening area, as was recommended by the *Standards for Water Works* [24], and the 58 holes, each with a diameter of 10 mm, were evenly distributed in the panel.

The effluent was withdrawn by seven submerged rectangular orifice tubes, with holes at the bottom. The bottom of each tube had 50 holes, with a diameter of 3 mm each, and the holes were placed at 3 mm intervals. Each tube was placed such that the orifices were positioned at the middle of each slot, which were created when the two inclined plates were inserted. The tubes were installed at the same locations in the clarifier without the inclined plates. The eight plates were placed at 40 mm intervals and were inclined at an angle of  $60^\circ$ , as depicted in Fig. 1.

In order to observe the effect of the inclined plate submergence, 237 mm high plates were used, with the top of the plates well below the surface of the water in the clarifier. To observe the effect from non-submerged plates, 260 mm high plates were used, with the top of the plates well above the water surface in the clarifier. In both instances, the effluent from each slot was withdrawn through a submerged orifice located at the center of the slot.

Fig. 1 shows the longitudinal side section and the top views of the rectangular clarifiers used in this study. In order to see the fluid movement in the clarifier, dye tests, using water-soluble dye, were performed at both clarifiers. An inflow of 2280 mL/min, corresponding to 0.5 h HRT (hydraulic retention time) was fed to both clarifiers simultaneously and the longitudinal side sections of both clarifiers were video-recorded to observe the effect of the inclined plates.

Thickened sludge from the K Water Treatment Plant, situated at Suwon city in S. Korea, was diluted with tap water, and was used as influent to evaluate the solid removal characteristics of both clarifiers. Twelve SS concentrations were prepared through



**Fig. 1.** Section and top views of laboratory scale rectangular clarifiers with and without inclined plates.

dilutions of thickened sludge, and the inflow to both clarifiers was adjusted to 0.5, 1, and 2h HRTs, corresponding to 0.57 m<sup>3</sup>/m<sup>2</sup>·h, 0.3 m<sup>3</sup>/m<sup>2</sup>·h, and 0.15 m<sup>3</sup>/m<sup>2</sup>·h SORs (surface overflow rates), respectively. The inflow was fed for at least three times the duration of each HRT to ensure the settling of the solids, before sampling the effluent for SS measurement. The same size pumping head was attached to the pump axis to ensure the same flow to each clarifier. Table 1 presents the specifications of the clarifiers and the inclined plates used in this study.

### 3. Results and Discussion

#### 3.1. Dye Test

The same dye inflow was fed to both clarifiers to observe the effect of the plates on the movement of fluid in the clarifier. Both submerged plates (237 mm high) and non-submerged plates (260 mm high) were inserted. Fig. 2 shows the section view of the clarifiers at 2280 mL/min of inflow, corresponding to 0.57 m<sup>3</sup>/m<sup>2</sup>·h SOR and 0.5 h HRT, with indicating (a) the clarifier without inclined plates, (b) the clarifier with the submerged inclined plates, and (c) the clarifier with the non-submerged inclined plates. The section views of dye distribution at 16, 21, and 23 minutes; at 15, 21, and 20 minutes; and at 20, 48, and 69 minutes after the start of the feeding are shown with no plates, submerged inclined plates, and non-submerged inclined plates, respectively. Initially, the dye on the water surface of the clarifier without the inclined plates, Fig. 2(a), flows to the submerged rectangular orifice tubes, from where it sequentially spreads across the entire longitudinal side section of the clarifier. After 23 minutes of feeding, the dye is spread throughout the section of the clarifier, proving that the effective HRT is very close to the calculated HRT. With the submerged inclined plates installed, as shown in Fig. 2(b), the dye flow is blocked by the first front upstream plate and is subsequently

**Table 1.** Specifications for Laboratory Scale Clarifier to Study the Effect of Inclined Plates

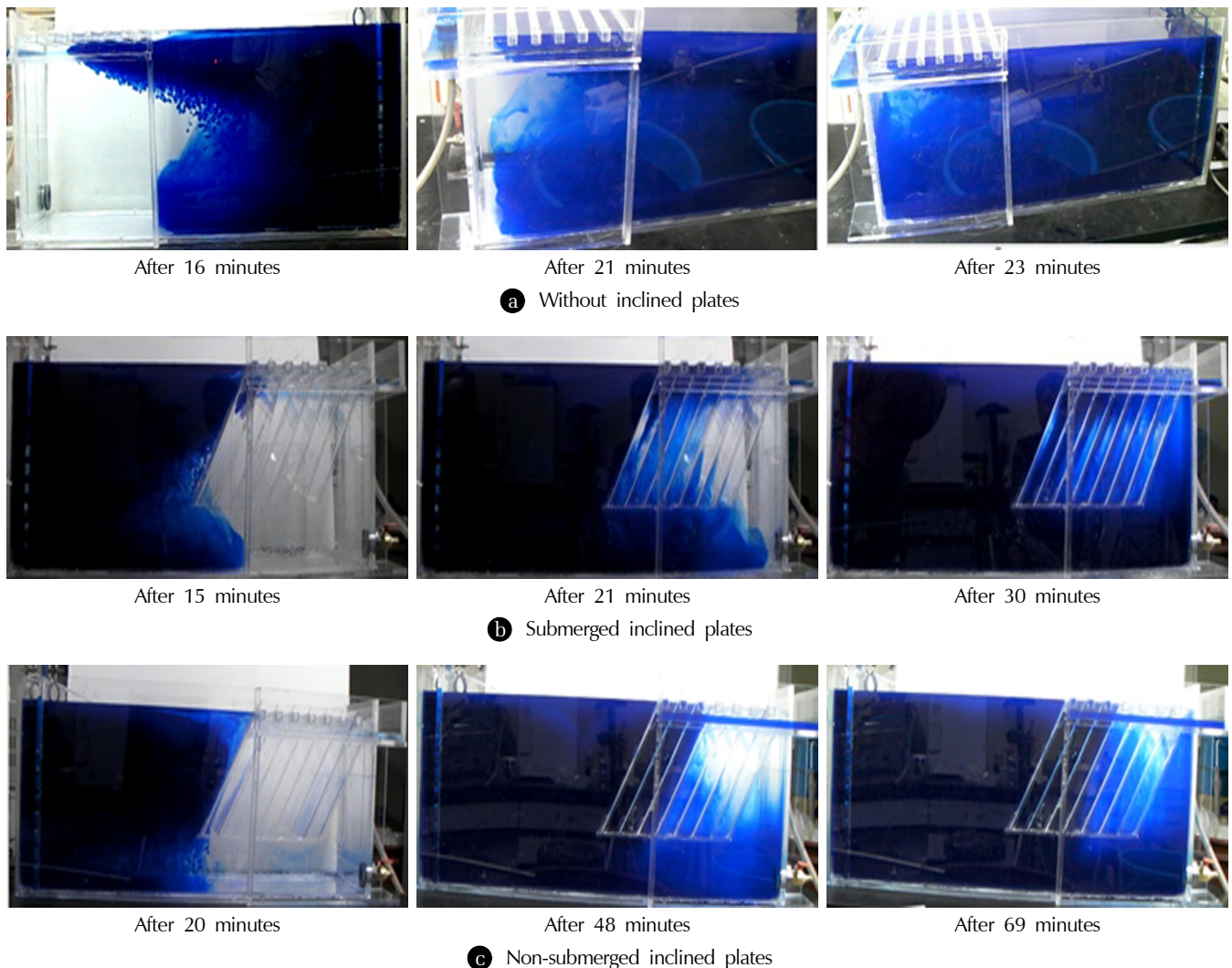
Item	Name	Specification	Remarks
Clarifier	Type	Rectangular	
	width, mm	300	
	Height, mm	350	
	Effective Height, mm	300	50 mm height for free board
	Length, mm	830	
Plate	Effective Length, mm	800	30 mm is for horizontal multi-hole diffuser plate
	Number	8	
Submerged	Width, mm	300	
	Length, mm	225	
Non-submerged	Width, mm	300	
	Length, mm	260	
Submerged rectangular orifice tube	Type	Rectangular	
	Number	7	
	Width, mm	15	
	Height, mm	15	
	No. of holes at each tube	50	
	Orifice diameter, mm	3	

moved to both the top and the bottom of the plates, after the dye has passed through the bottom of the first plate. The video of the dye movement in this clarifier shows that the simultaneous flow of a portion of the dye from the top down to the bottom and from the bottom up to the top takes place through the inclined slots created by the plates, while a portion of the dye at the top flows directly to the orifice as effluent. The collision of the two flows within the same slot is believed to hamper the settling of solids, and the flow at the top of the submerged inclined plates becomes effluent, without settling.

When the plates are not submerged, as shown in Fig. 2(c), the dye flow is initially blocked by the first front upstream plate, similar to the instance of the submerged plates. However, after the dye has passed through the bottom of this front plate, it spreads onto the bottom of the plates and sequentially flows toward the top of the plates through the inclined slots. The dye at the top of the plates is the effluent at trough in this figure. As shown

in these pictures, the dye injected into the clarifier with the non-submerged inclined plates flows toward the top of the clarifier through the slots. However, the dye flow is restricted to the front three slots only and does not flow through all the slots. Moreover, the flow to the slots proportionally decreases toward the downstream slots. Since more dye flow represents a denser color, the densest color at the upstream front slot shows that the highest flow occurs at this slot.

It is shown that even after 69 minutes, i.e., 2.3 times longer than the 30 minutes HRT, only the front three slots have received the dye flow. From this observation, it is assumed that only a few front slots will receive the flow if inclined plates are installed as instructed by the *Standards for Water Works* [24]. Although these standards do not specify that the inclined plates be submerged, the unidirectional water flow within the slots, essential to the settling of solids, cannot be expected when the inclined plates are submerged, and doing this should therefore be avoided.



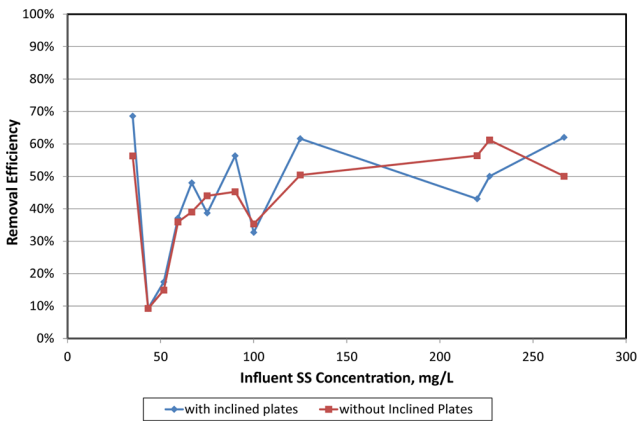
**Fig. 2.** Dye test results from clarifier without inclined plates, clarifiers with submerged and non-submerged inclined plates when surface overflow rate is  $0.57 \text{ m}^3/\text{m}^2\cdot\text{h}$ .

The differences of the head loss from flow to each slot could be the cause for only a few front slots receiving the flow. Since the submerged orifices are located below water surface level and at the middle of slot, the flow to each slot becomes individual and head loss from flow to slot is proportionally increased as the distance between the front end of clarifier and respective slot is increased. In this experiment, it is observed that only the upstream three of the seven slots receive the flow, with the first upstream slot having the highest flow. In order to enable the Boycott effect at every slot, each of the slots should receive equalized flow, as explained in detail by Hane-Weijman [15]. Therefore, the simple insertion of inclined plates, as described in the *Standards for Water Works* [24], cannot be expected to enable high solid removal efficiency by utilizing the Boycott effect, as is verified by the SS removal tests.

### 3.2. Suspended Solids (SS) Removal Characteristics

Since the dye tests have confirmed that the Boycott effect cannot be utilized in submerged inclined plates that have both upflow and downflow within the slots, the SS removal characteristics of the clarifier with the non-submerged inclined plates were compared with those of the clarifier without plates. Each clarifier was supplied with identical wastewater at the same flow rate. Three different SORs and 12 different SS concentrations at each SOR were tested to observe the effect of the inclined plates.

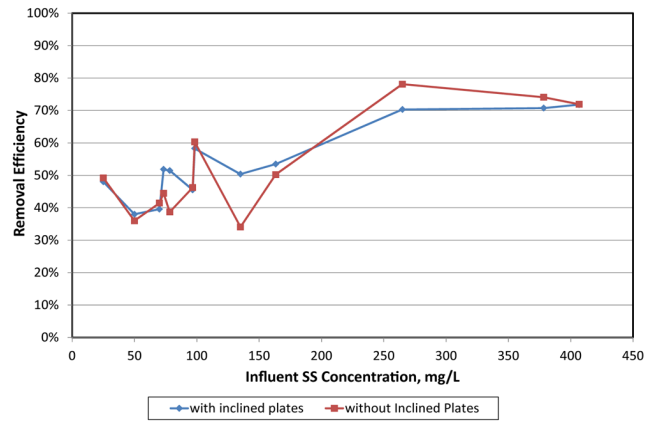
The SS removal efficiencies with respect to the influent SS concentration at 0.57 m<sup>3</sup>/m<sup>2</sup>·h SOR are shown in Fig. 3. The clarifier with the plates has approximately 10 p.p. (percentage points) higher removal efficiency than has the clarifier without the plates when the influent SS concentrations are 35, 67, 90, 125, and 267 mg/L, respectively. In contrast, the clarifier without the plates shows an increase in removal efficiency of more than 10 p.p. at 220 and 226.7 mg/L of influent SS concentrations. The removal efficiencies are the same or less at the rest of the influent SS concentrations at both clarifiers. The average SS removal efficiencies of the clarifier with plates and the clarifier without plates are 43.7 and 41.5%, respectively, with the clarifier with plates showing 2.2 p.p. higher average removal efficiency.



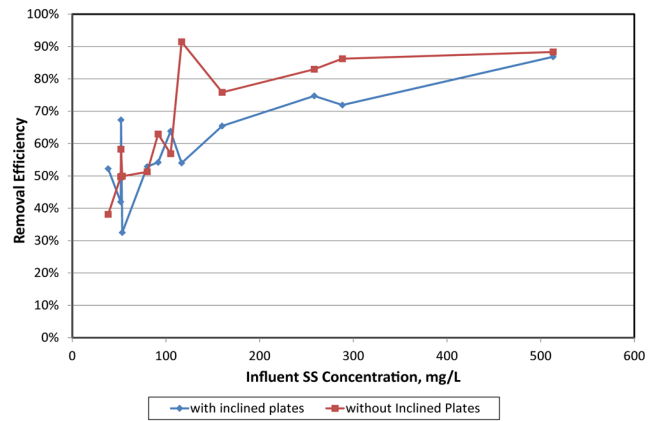
**Fig. 3.** Suspended Solid removal efficiencies at clarifiers with and without non-submerged inclined plates when surface overflow rate is 0.57 m<sup>3</sup>/m<sup>2</sup>·h

Fig. 4 shows the SS removal efficiencies with respect to the influent SS concentrations at 0.30 m<sup>3</sup>/m<sup>2</sup>·h SOR. The clarifier with plates shows 7.4, 12.7, and 16.3 p.p. higher removal efficiencies in comparison with the clarifier without plates when the influent SS concentrations are 73.3, 78, and 135 mg/L, respectively. In contrast, the clarifier without plates has 7.8 p.p. higher SS removal efficiency at 265 mg/L of influent SS concentration. The difference in the removal efficiencies is less than 5 p.p. at the rest of the influent SS concentrations. The average SS removal efficiency of the clarifier with and the clarifier without the plates are 54.1 and 52.1%, respectively, and the clarifier with plates shows an average removal efficiency of 2.0 p.p. higher.

The SS removal efficiencies with respect to an influent SS concentration at 0.15 m<sup>3</sup>/m<sup>2</sup>·h SOR are shown in Fig. 5. The clarifier with plates has a range of 7 to 14 p.p. higher removal efficiency than has the clarifier without plates when the influent SS concentrations are 38.3, 52.0, and 105.0 mg/L. In contrast, the clarifier without plates has a range of 8 to 17 p.p. higher removal efficiency than has the clarifier with plates when the influent SS concen



**Fig. 4.** Suspended Solid removal efficiencies at clarifiers with and without non-submerged inclined plates when surface overflow rate is 0.3 m<sup>3</sup>/m<sup>2</sup>·h.



**Fig. 5.** Suspended Solid removal efficiencies at clarifiers with and without non-submerged inclined plates when surface overflow rate is 0.15 m<sup>3</sup>/m<sup>2</sup>·h

trations are 51.7, 53.3, and 91.7 mg/L, respectively. When the influent SS concentration is above 117 mg/L, the clarifier without plates consistently has higher removal efficiency than has the clarifier with plates. The average SS removal efficiencies of the clarifier with and the clarifier without plates are 59.8 and 66.0%, respectively, and the clarifier without plates shows an average of 6.2 p.p. higher removal efficiency.

As shown in Figs 3–5, the clarifier with the inclined plates, designed as described in the *Standards for Water Works*, does not show superior SS removal efficiencies compared with the clarifier without plates. At the lowest SOR of  $0.15 \text{ m}^3/\text{m}^2\cdot\text{h}$ , the clarifier without plates even shows a higher average SS removal efficiency compared with the clarifier with plates, as shown in Fig. 5. At this SOR, the clarifier without plates consistently shows higher SS removal efficiencies at SS concentrations above 117 mg/L of influent. In this study, each slot of the inclined plates received inflow from the bottom of the slot (upflow) and the settled sludge was moved down to the bottom of the clarifier along the bottom plate at each slot. The upflow of the inflow and the downflow of the settled sludge collide in the slots, which is believed to cause the resuspension of the settled sludge. The consistently lower SS removal efficiencies of the clarifier with the inclined plates could be ascribed to the resuspension of the settled solids in the slots. These results indicate that the application of inclined plates in the clarifier reduced the SS removal capacity, rather than improving it.

Fig. 6 shows the overall SS removal efficiencies with respect to influent SS concentrations at three different hydraulic loading rates. With the inclined plates installed, as shown in Fig. 6(a), the removal efficiencies are proportionally increased with the influent SS concentrations when the concentration is more than 100 mg/L at all SORs. However, the removal efficiency differences are not significant when the SS concentrations in the influent are less than 100 mg/L. From these data, it is assumed that higher SS loading promotes the coagulation of particles, which enhances the solid removal efficiency, due to the high concentrations of coagulants in the influent. As mentioned in the Experiments section, the influent in this study was derived from the thickened sludge from the water treatment plant, with numerous coagulants added through the water treatment process. The influent containing the higher SS concentration has more coagulants that promote the coagulation of particles in the clarifier. As the SOR is less, the removal efficiency is enhanced, since more HRTs provide more time for settling. The figure shows that the clarifier with the plates follows this tendency.

With the inclined plates not installed and the influent SS concentrations below 100 mg/L, as shown in Fig. 6(b), the SS removal efficiency is proportionally increased at the lowest influent SS concentration of SOR  $0.15 \text{ m}^3/\text{m}^2\cdot\text{h}$ . When the influent SS concentrations are more than 100 mg/L, the two hours of HRT and the higher solids loading are assumed to promote the coagulation of particles and provide settling time, which cause a sharp increase in the solid removal efficiency. At 0.3 and  $0.57 \text{ m}^3/\text{m}^2\cdot\text{h}$  SORs, corresponding to 1 and 0.5 hours of HRTs, respectively, there is no sharp increase of SS removal efficiency at 100 mg/L of influent SS concentration. This is believed to be attributable to a short HRT, which does not provide enough time for settling. The SS

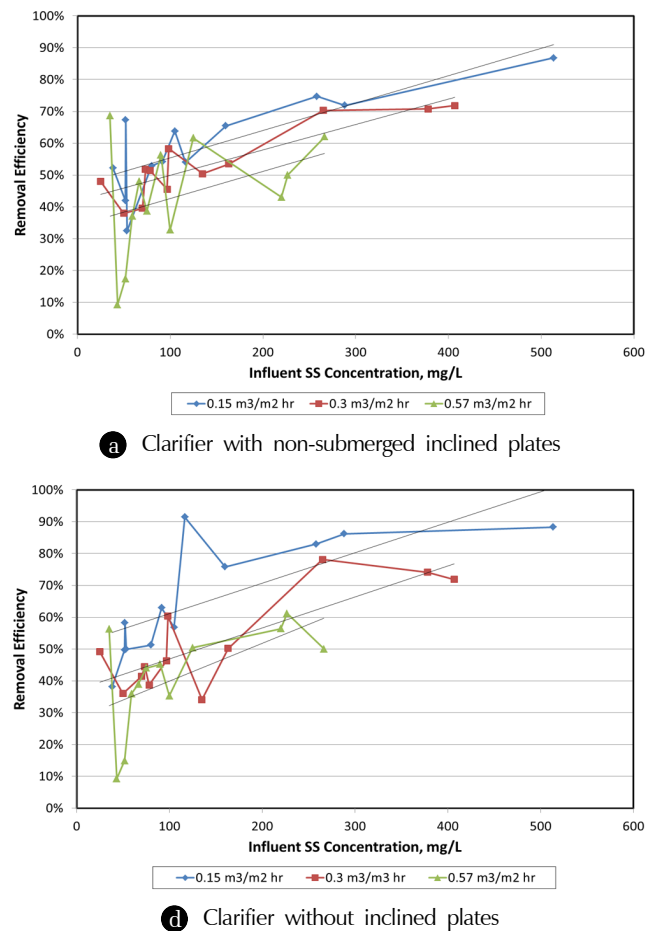


Fig. 6. SS removal efficiencies at three different surface overflow rates.

removal efficiencies proportionally increase with the influent SS concentrations until the influent SS concentration reaches 200 mg/L. The SS removal efficiency drops after the influent SS concentrations increase to more than 200 mg/L, and it is believed that the short HRT cannot manage the increased solid loads and therefore the solids are carried over to the effluent.

When the operational results from the two clarifiers are compared, it seems that the inclined plates in the clarifier do not promote solids removal, and the results even indicate a decline in the removal efficiency of this clarifier. It is believed that the polarization of inflow to a few front slots and the collision of two flows in the same slot cause the decline in the solid removal efficiency.

It is assumed that the projected area from the inclined plates plays a role in the settling, in addition to the water surface area [6]. In the dye test with  $0.57 \text{ m}^3/\text{m}^2\cdot\text{h}$  SOR, the upstream first three slots are shown to receive inflow and, from this observation, it is believed that a maximum of three inclined plates participates in the solid settling. The projected area from one inclined plate is calculated at  $69,000 \text{ mm}^2 \times \cos 60^\circ = 35,500 \text{ mm}^2$ , since the surface area of one plate is  $69,000 \text{ mm}^2$ , the angle of the water surface is  $60^\circ$ , and the total projected area of three plates is  $103,500 \text{ mm}^2$ .

The effective surface area for settling in the clarifier with the inclined plates is the sum of the water surface area and the total projected areas. Since the water surface area is  $240,000 \text{ mm}^2$ , the effective surface area is  $240,000 \text{ mm}^2 + 103,500 \text{ mm}^2 = 343,500 \text{ mm}^2$ , when three slots are assumed to be involved in the settling. The projected area from three inclined plates, that is  $103,500 \text{ mm}^2$ , is 69.9% of the surface area and, therefore, the inclined plates provide a maximum of 1.43 times more surface area for settling than the clarifier without inclined plates. Although the clarifier with inclined plates has more surface area for settling, it appears that the inclined plates inserted into the clarifier do not promote settling. Occasionally, the inclined plates even inhibit settling, as shown by the results from Samstag et al [27]. In order to verify the results from this study and the work of Samstag et al [27] under field conditions, it is recommended that full-scale experiments must be conducted. Such experiments should comprise treating identical untreated water in both the clarifier with the inclined plates and the clarifier without the inclined plates under the same operational conditions. The inclined plates in the full-scale experiment have to be installed according to the procedure indicated by the *Standards for Water Works* [24].

The results of the dye tests and the SS removal experiments in this study, however, indicate important factors when inclined plates are considered to enhance settling in a clarifier, as described by the National Swedish Environmental Board [15] and Hendricks [14]. These factors are (1) equalized flow to each of the slots created by the inclined plates and (2) inflow to the center of each of the slots.

## 4. Conclusions

Two identical laboratory-scale rectangular clarifiers were constructed and eight inclined plates were inserted into one of the clarifiers, as proposed in the *Standards for Water Works* [24]. After the treatment of same wastewater at identical inflow rates, the findings are as follows:

- 1) When the inclined plates submerged, both the top and the bottom of the slot created by the plates received the inflow simultaneously and the Boycott effect could not be utilized in this situation. Therefore, the inclined plates should not be submerged and the supernatant from each slot has to be withdrawn from the top of each slot.
- 2) It has shown that the SS removal efficiencies of the clarifier with the inclined plates are not superior to that of the clarifier without the inclined plates, although the clarifier with the inclined plates has been constructed as described in the *Standards for Water Works* and claims to have large surface area including projected area from plates for SS settling. It is assumed that the inflow to only a few front slots and the countercurrent flow of the inflow and the settled solids in the slots cause the weakening of the Boycott effect.
- 3) Provisions to maximize the Boycott effect have to be added to the *Standards for Water Works* [24], which propose the design procedure for a clarifier with inclined plates. Such provisions include equalized inflow to each slot created by

the plates, withdrawing supernatant from an individual slot, and inflow to the center of the slot to avoid the collision of inflow with the settled solids that slide down to the bottom of the clarifier.

## Acknowledgements

This work was supported by the Kyonggi University Research Grant 2013. The author wishes to acknowledge the help received from Dong-Kun Oh, Jae-Sung Lee, and Chan-Hui Cho from the Department of Environmental Energy Engineering of the Kyonggi University.

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