Analyzing the design criteria of primary settlers for small sewage treatment systems: A national survey in Taiwan

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ABSTRACT

An onsite wastewater treatment facility normally has a treatment capacity of 5–200 population equivalents (PE). The small system is receiving increasing attention in Asia countries to make up for the shortage of public sewer system. While many countries rely on large centralized system, small systems in Taiwan have significantly contributed to the treatment of municipal wastewater (21.6%) to make up for the low sewer connection (17.0%). To resolve disputes on the design criteria of primary settlers in small systems recommended by the government, a nationwide survey of 350 permit applications were conducted. The result of the survey revealed that 53% adopted self-proven criteria to reduce the size of the primary settlers using a design flow rate \(Q_o\) of 10 m\(^3\)/d or less. The official design criteria were thus analyzed by using two new approaches of design criteria, scale-down factor and sludge blanket height ratio, as proposed in this study. The analysis indicated that sizing of primary settlers must consider the diurnal flow fluctuation and storage of settled sludge in primary settlers for a sufficient period of time, preferably up to 6 months. The official design criteria may be too conservative for \(Q<5\) m\(^3\)/d, but inadequate for \(Q>20\) m\(^3\)/d. Based on the result of this study, new measures are suggested to strengthen the onsite program.

1. Introduction

An onsite wastewater treatment facility normally has a treatment capacity of 5–200 population equivalents (PE). Many countries have established a variety of onsite treatment programs for the purpose of comprehensive environmental protection as in the USA [1–3], for sustainability of urban sanitation as in Europe [4], for backing up areas remote to the public sewer system as in Japan [5–6], and for coping with increasing water demand problems as in the Middle East and North Africa [7]. In Guangzhou, China, the onsite systems were also evaluated for cost effectiveness as compared to public sewer system [8]. Recently, onsite systems are receiving increasing attention in many Asia countries to make up for the shortage of the public sewer system. Table 1 shows the treatment percentages of public sewer and onsite systems in Taiwan and Japan. In 2007, the decentralized onsite system (medium and small system) has contributed 21.6%, exceeding the public sewer of 17.0% in Taiwan.

There are several different design approaches for onsite treatment systems. One of the onsite treatment systems is the Asia onsite system (also called “Johkason” in Japanese) which is used to treat grey water and toilet flushes [9–10]. As shown in Fig. 1, the system typically consists of several unit processes (primary settling, aeration, final settling, and disinfection) in one prefabricated module. The settled sludge in the final settlers is pumped back to the primary settlers for storage. The system is essentially equivalent to the Model Program 3 of “Management through operating permit” set forth by USEPA [2,11] or to the Part 12566-3 of “Packaged and/or site assembled domestic wastewater treatment plant” regulated in Europe Union [12].

In 1999, Taiwan initiated a new program for onsite wastewater treatment systems (OWTS) and placed the responsibility on the construction of these systems on the building developers. The program consists of a small system to replace the old septic tank system. Under this program, a newly constructed building must install an OWTS to meet the national effluent standards if no existing public sewer system is accessible to the site. Applicants might choose not to follow the official criteria if self-proven designs submitted for reviews were determined to be adequate after passing a functional test. Applicants often use the self-proven approach in an attempt to scale-down the system, particularly the primary settlers, to save the land space for installation. The smaller or shallower primary settlers may cause deterioration in effluent quality due to a higher sludge blanket as the settled sludge is build up and not withdrawn out of the unit in time. Often the authority was caught in an awkward situation, because the committee had difficulty in justify-
ing the variety of self-proven criteria. Moreover, the procedure and testing conditions were not well specified for the functional test.

In Taiwan, a manual of technical criteria for the design and construction of onsite system has been recommended by the Taiwan Construction and Planning Agency (TCPA) [10]. The criteria basically follow the principles set by the Japan Architecture Center (JAC) [9]. However, the design concept and criteria were promulgated with little support of data in literature. Many of these onsite systems have been installed based on empirical operation results [5,13]. To resolve disputes of the two design approaches, a nationwide survey of onsite permit applications were conducted to evaluate the design criteria for the small systems, particularly for primary settlers. In this study, two new approaches, the scale-down factor method and the sludge blanket height ratio method, were proposed for the theoretical analysis of primary settlers for the onsite systems.

2. Methods

2.1. National survey

A survey instrument was designed to extract information from permit applications of the small onsite systems. The key issues addressed in the survey included type of treatment, design capacity, type of configuration, dimensions of the unit, and material of fabrication. Another purpose of the survey was to assess the so-called self-proven criteria in the applications which were deviations from the official criteria. A total of 350 design units were analyzed, accounting for 72% of the total applications submitted for permit review from May 1999 to May 2002.

2.2. Analysis of design criteria for primary settlers

Analysis was made on primary settlers using the design equations recommended by TCPA as follows [10]:

for the “Separate Contact Aeration” (SCA) process ($Q \leq 10 \text{m}^3/\text{d}$),

\[
V_d = 2.5, \quad \text{if } Q \leq 1 \quad (1A)
\]

\[
V_d = 2.5 + 2.5(Q - 1), \quad \text{if } 1 < Q \leq 2 \quad (1B)
\]

for the “Contact Aeration” (CA) process ($Q > 10 \text{m}^3/\text{d}$),

\[
V_d = 5 + 1.25(Q - 2), \quad \text{if } 2 < Q \leq 10 \quad (1C)
\]

\[
V_d = 1.5qn \times 1.1, \quad \text{if } 51 < n \leq 100 \quad (2A)
\]

\[
V_d = [150q + q(n - 100)] \times 1.1, \quad \text{if } 100 < n \leq 200 \quad (2B)
\]

\[
V_d = [250q + 0.5q(n - 200)] \times 1.1, \quad \text{if } n > 200 \quad (2C)
\]

where $V_d$ is volume in m$^3$, $q$ is design flow rate per person (0.25 m$^3$/d), $n$ is the number of heads, and $Q$ is total flowrate ($q \times n$). A computer spreadsheet was formulated to compute hydraulic detention time ($HDT = V_d/Q$) vs. $Q$ for a range of persons ($n = 3$–300, or $Q = 0.75$–75 m$^3$/d) by using Eqs. (1A)–(1C) and (2A)–(2C) for the SCA process and CA process, respectively. The effective water depth ($H_e$) of primary settlers is assumed to be 1.5 m and 1.8 m as required by the TCPA criteria for the SCA process and the CA process, respectively, to compute overflow rate ($OR = H_e/HDT$) vs. $Q$. These two sets of data were then analyzed using a nonlinear regression technique of power function to obtain the equations of $HDT$ vs. $Q$ and $OR$ vs. $Q$, respectively.

2.3. Analysis for scale-down factor and sludge accumulation

Two new rational methods were developed in this study to examine the appropriateness of the official design criteria for the primary settlers. The first is the scale-down factor (SF) method which is defined as follows:

\[
SF = \frac{OR_{\text{for large systems}}}{OR_{\text{for small systems}}} \quad (3)
\]

where $OR$ is the overflow rate in m$^3$/m$^2$-d. Although the design concept is different between the two systems, $SF$ is used for small systems to account for diurnal influent fluctuation and short-circuiting associated with sludge accumulation and uneven inlet/outlet arrangement in primary settlers. Typical design criteria were obtained from the literature for two large systems [14–15].

The equation of the second method was derived below to estimate the sludge volume accumulated for a maximum allowable time of 180 days as required by the official TCPA criteria. The daily sludge accumulation rate of the settled primary sludge ($dM_1/dt$) and the secondary sludge ($dM_2/dt$) withdrawn from the final settler can be calculated below:

\[
\frac{dM_1}{dt} = nqX_{R_e} \quad (4A)
\]

\[
\frac{dM_2}{dt} = nqY_{S}(1 - R_s) \quad (4B)
\]

where $X$ is influent SS concentration (300 mg/L), $S$ is influent BOD$_5$ concentration (250 mg/L), $Y$ is growth yield coefficient (0.55), $R_e$ is SS removal rate in primary settling (30%), and $R_s$ is BOD$_5$ removal rate in primary settling (20%).

Assuming a digestion ratio ($D_e$) due to anaerobic degradation, the net total mass ($M$) of sludge (primary and secondary) accumulated in primary settlers during a period of maximum storage time

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td><strong>Comparison of treatment percentage by the public sewer and onsite systems.</strong></td>
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<tr>
<td>Treatment system</td>
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<tr>
<td>Public sewer system (%)</td>
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<tr>
<td>Medium system (%)</td>
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<tr>
<td>Small system (%)</td>
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<tr>
<td>Total (%)</td>
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</table>

*a Source: JMOE [6].

*b For the agricultural community system in Japan.

*c For the household “Johkason” system in Japan, possibly including the medium OWTS as used in Taiwan.

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For the agricultural community system in Japan.

Source: JMOE [6].

\[ V_d = 5 + 1.25(Q - 2), \quad \text{if } 2 < Q \leq 10 \quad (1C) \]

\[ V_d = 1.5qn \times 1.1, \quad \text{if } 51 < n \leq 100 \quad (2A) \]

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2.3. Analysis for scale-down factor and sludge accumulation

Two new rational methods were developed in this study to examine the appropriateness of the official design criteria for the primary settler. The first is the scale-down factor (SF) method which is defined as follows:

\[ SF = \frac{OR_{\text{for large systems}}}{OR_{\text{for small systems}}} \quad (3) \]

where $OR$ is the overflow rate in m$^3$/m$^2$-d. Although the design concept is different between the two systems, $SF$ is used for small systems to account for diurnal influent fluctuation and short-circuiting associated with sludge accumulation and uneven inlet/outlet arrangement in primary settlers. Typical design criteria were obtained from the literature for two large systems [14–15].

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\[ \frac{dM_1}{dt} = nqX_{R_e} \quad (4A) \]

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where $X$ is influent SS concentration (300 mg/L), $S$ is influent BOD$_5$ concentration (250 mg/L), $Y$ is growth yield coefficient (0.55), $R_e$ is SS removal rate in primary settling (30%), and $R_s$ is BOD$_5$ removal rate in primary settling (20%).

Assuming a digestion ratio ($D_e$) due to anaerobic degradation, the net total mass ($M$) of sludge (primary and secondary) accumulated in primary settlers during a period of maximum storage time
(T_s) can be calculated below:

\[ M = \left( \frac{dM_1}{dt} + \frac{dM_2}{dt} \right) (1 - D_s) T_s \]  

where \( D_s \) is the digestion rate of settled sludge (35%) and \( T_s \) is the maximum storage time (180 days as required by the TCPA design criteria).

By assuming a ratio \( r_s \) of the sludge blanket height relative to the effective tank height, the volume of the primary settler can be estimated as follows:

\[ V_s = \frac{mQ[XR_s + YS(1 - R_s)][1 - D_s]T_s}{\rho_s r_s} \]  

where \( V_s \) is the estimated volume of primary settlers in m³ based on the requirement of sludge accumulation, \( \rho_s \) is the bulk density of settled sludge (2%). All the values in the parentheses were typical values from literature [13,15–16]. Three \( r_s \) values (30%, 40%, and 50%) were used to estimate \( V_s \) and the corresponding \( HDT \).

The two sets of \( HDT \) vs. \( Q \) data points estimated in Section 2.2 required by the TCPA criteria and Section 2.3 to check for sludge blanket height, respectively, were superimposed on the same diagram for comparative analysis.

3. Results and discussion

3.1. Market analysis

The results of the survey showed that 53% of applicants adopted the self-proven criteria, implying that the market was in favor of small-scale designs to reduce the land area that would be required by using the more stringent official criteria, comparing with the self-proven criteria. This preference was also evidenced by the fact that 70% of the design flow rates were 20 m³/d (80 heads) or less. Fig. 2 shows the percentage distribution of the design flow rates covered by this study. The allowance of self-proven design criteria also caused serious problems due to inconsistency in the committee’s review, including inadequate volume and depth (<1.5 m), improper inlet and outlet designs, and excessive sludge accumulation in primary settlers. The design of primary settlers posed the most serious dispute in all treatment processes, primarily due to poor recognition of storage requirement for the settled sludge. Also, the small system applicants often mistakenly adopted the overflow design criteria for large systems, disregarding serious short-circuiting associated with uneven hydraulic distribution over the surface area due to lack of equalization and poor inlet and outlet arrangement in primary settlers [13].

As shown in Fig. 3, the two most commonly used treatment methods were the “Separate Contact Aeration” (45.3%) and the “Contact Aeration” (41.9%). As to the fabrication material, 74.1% were made of fiber reinforced plastic (FRP) and 17.1% of reinforced concrete (RC) to cope with the frequent earthquake in the island. A majority (65.2%) of the small systems were designed within one unit. The rest (34.8%) were configured with multiple units and connected by piping, which might suffer from breakage in an earthquake event. When applications were rejected, the reasons given by the committee were inadequate functional test (30.4%), inadequate design (28.3%), and using inadequate self-proven criteria (21.7%). Most of reviewers indicated that functional tests were not conducted under diurnal loading condition and the test time was too short to allow for adequate sludge accumulation. European Union (EU) requires the system to be tested under regular loading over a period of 38 weeks after the system has developed full efficiency [12]. The EU system is also tested in a series of stress conditions, including under loading, over loading, and loss of power.

3.2. Scale-down factor analysis

Fig. 4 gives the nonlinear regression result of \( OR \) vs. \( Q \), using the official design criteria for the separate contact aeration process (\( Q \leq 10 \text{ m}^3/\text{d} \)) and the contact aeration process (\( Q > 10 \text{ m}^3/\text{d} \)). The result shows a power function of \( OR = 0.554 Q^{-0.2416} \) with a fair correlation coefficient of \( R^2 = 0.9558 \). Table 2 compares four design criteria of primary settlers for two small systems used in Taiwan.
Fig. 4. Results of nonlinear regression of overflow rate (OR) vs. design flowrate (Q) of primary settlers for small systems, using the design criteria with an effective height of 1.5 m for the separate contact process and 1.8 m for the contact process as required by the official TCPA guidelines (1998).

[10] and two large systems used in USA [14–15]. It can be seen that, when comparing with large systems, OR is in a rather narrow and small range of 0.5–1.6 m³/m²-d for the average flowrate of 0.75–75 m³/d (or PE = 3–300 heads) for small systems. For large systems, it is important to note that the OR criteria are affected by two situations: (1) if the system uses recirculation via returning activated sludge (RAS), and (2) if average flowrate (Qave) or peak flowrate (Qpk) is used in design.

Using an OR of 0.5–1.6 m³/m²-d for small systems and 40 m³/m²-d (based on Qave without recycling) for the large systems indicated in Table 2, a scale-down factor (SF) of 25–80 can be calculated. A peak factor (PF = Qpk/Qave) can be estimated of 2.0–4.2 using PF = (18 + √P)/(4 + √P) for large systems as proposed by Ten-State Standards [14], in which P is in 1000 heads. It appears that the SF is much larger than the PF for large centralized systems. It implies that an additional safety factor of approximate 6–20 (25–80/4) is used in the TCPA’s criteria to account for diurnal inflow fluctuation and short-circuiting associated with sludge accumulation and the inlet and outlet arrangement in primary settlers for small systems.

According to the TCPA’s design criteria, primary settlers are required to partition into two chambers with the first chamber being two-thirds of the total effective clarifier volume (Fig. 1). A minimum effective height (He) of 1.5 m is required for the settler. To avoid short-circuiting, a submerged depth of 1/3 He is required for the inlet pipe and 1/2 He for the outlet pipe. However, if the settler has a circular cross-section, the submerged depth can be reduced to 1/4 He for the inlet pipe and 1/3 He for the outlet pipe. Without the partition, the effective HDT can be reduced by 25% of its theoretical value in a tracer study [13].

3.3. Sludge accumulation analysis

By using the TCPA’s design criteria for a range of design flowrates (Section 2.3), a set of HDT and Q data were obtained for primary settlers. The data set were analyzed by a nonlinear regression technique and the result shows a negative power function of HDT = 62.447 Q^{-0.1869} (R² = 0.8744). All the data points (n = 350) obtained from the survey were also plotted in Fig. 5. Most of the data points fall below the regression curve, suggesting that most of primary settlers approved were under-sized with shorter HDTs, when comparing with the design according to the official criteria.

The HDT requirement is further analyzed for sludge accumulation and the height of settled sludge accumulated for 6 months must not exceed the submerged depth (1/2 He or r = 50%) of the outlet pipe. If this is violated, it is likely that the sludge settled in primary settlers will be carried out of the outlet pipe and degrades the effluent quality. Using the values stated in Section 3, a constant number of 0.13 kg/m³ can be calculated for the term of [(X/Rs) + (Y/S)(1 – Rs)] (1 – Ds) in Eq. (4), suggesting that a net 0.13 kg of sludge is produced for every m³ of flow treated during 6 months of operation. This value is close to the values reported in the literature [15]. It is interesting to note that the HDT requirement based on sludge accumulation is independent on design flowrate with three horizontal lines shown in Fig. 5, each at a sludge height ratio (r) of 30%, 40%, and 50%, respectively.

As also shown in Fig. 4, for Q ≤ 10 m³/d, the HDT requirement by the official criteria ranges from 42 to 70 h with a r of 45% or less after 6 months of operation. For Q < 5 m³/d, the HDT requirement

Table 2

Comparison of design criteria of primary settlers for small and large sewage treatment system.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Small system</td>
<td>Small system</td>
<td>Large system</td>
<td>Large system</td>
</tr>
<tr>
<td>Overflow rate w/o RAS (m³/m²-d)</td>
<td>(≤10 m³/d)</td>
<td>(10–1000 m³/d)</td>
<td>(≥1000 m³/d)</td>
<td>(≥1000 m³/d)</td>
</tr>
<tr>
<td>Overflow rate with RAS (m³/m²-d)</td>
<td>Not available</td>
<td>Not available</td>
<td>Not available</td>
<td>Not available</td>
</tr>
<tr>
<td>Hydraulic detention time (hr)</td>
<td>36–80b</td>
<td>26–40°</td>
<td>250</td>
<td>1.5–2.5</td>
</tr>
<tr>
<td>Weir loading rate (m³/m²-d)</td>
<td>Not available</td>
<td>Not available</td>
<td>(Qₚ ≤ 3800 m³/d)</td>
<td>(Qₚ &gt; 3800 m³/d)</td>
</tr>
<tr>
<td>Effective height (m)</td>
<td>1.8–4.0</td>
<td>1.5</td>
<td>≥2.1</td>
<td>3.0–4.9</td>
</tr>
<tr>
<td>Free board (cm)</td>
<td>≥20</td>
<td>25–45</td>
<td>≥3</td>
<td>N/A</td>
</tr>
<tr>
<td>Inlet, outlet submerging depth (m)</td>
<td>1/3, 1/2 Heₐ</td>
<td>1/3, 1/2 Heₐ</td>
<td>≤0.3</td>
<td>0.3–0.45 (Qₚ)</td>
</tr>
<tr>
<td>Horizontal velocity (m/s)</td>
<td>Not available</td>
<td>Not available</td>
<td>≥0.3</td>
<td>≤0.75 (Qₚ)</td>
</tr>
<tr>
<td>Bottom slope (%)</td>
<td>Required, not specified</td>
<td>Required, not specified</td>
<td>Not available</td>
<td>6–16</td>
</tr>
</tbody>
</table>

a SCA denotes the separate contact aeration process; CA denotes the contact aeration process.
b Analyzed by this study using the design criteria recommended by TCPA [10].
The design of primary settlers for small systems must consider diurnal flow fluctuation and storage of settled sludge for a period of at least 6 months. Accordingly, two approaches for technical analyses (scale-down factor and sludge accumulation) were performed in this study to evaluate the appropriateness of the official design criteria for primary settlers. The study indicated that, for $Q \leq 10 \text{ m}^3/\text{d}$, a primary settler of a 42 h $HDT$ and $1.5 \text{ m} H_s$ should be sufficient for the separate contact aeration process. However, for $Q > 20 \text{ m}^3/\text{d}$, the official $HDT$ design criteria may pose a risk of excessive sludge accumulation ($r_s > 50\%$) in primary settlers for the contact aeration process after 6 months of operation.

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