DESIGN OF MULTI-STORY SEWAGE TREATMENT FACILITIES

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ABSTRACT

In Osaka City, due to rises in land prices and the rapid advances of urbanization, it is difficult to enlarge sites for sewage treatment facilities. To enhance efficient land utilization, construction of multi-story facilities has been promoted. This effort commenced with the building of a two-story primary settling tank, followed by two-story final settling tanks, aeration tanks vertically combined with final settling tanks and three-story final settling tanks. Together with the introduction of these multi-story facilities, efforts have also been made to further deepen the aeration tanks.

One of the features of the city’s multi-story sewage treatment facilities is the use of outlet pipes for purified wastewater in the final settling tanks. This has helped promote introduction of multi-story facilities. These multi-story facilities in Osaka City have already been in operation for ten to twenty years under satisfactory treatment conditions.

The area occupied by a multi-story structure is only 46% that of conventional single-story structures. Construction cost for single- and multi-story structures is almost equal.

KEYWORDS

Land use efficiency; sewage treatment plant; waste water treatment facilities; multi-story facilities; three-story final settling tank; and outlet pipe

INTRODUCTION

Efforts to obtain sites for sewage treatment plants in Osaka City commenced in the 1920’s. By the mid-1960’s, the majority of the land for the present twelve plants was secured. Efforts are being continued to enlarge existing sites, although due to rises in land prices and rapid urbanization, it is becoming extremely difficult to purchase more land. Meanwhile, sewage inflow has increased above originally planned levels as a result of urbanization and enhanced living standards, giving rise to the necessity to treat a large volume of sewage with limited treatment area.

In the mid-1960’s, construction of multi-story facilities commenced as circumstances required, leading to the current situation in which every sewage treatment plant uses some kind of multi-story facility for sewage treatment. In Osaka City as calculation shows, average site area required for treatment capacity of 1 m$^3$/day is as small as 0.29 m$^2$.

This paper introduces multi-story sewage treatment facilities in Osaka City as a reference when obtainment or enlargement of treatment site is difficult.
STRUCTURE OF MULTI-STORY FACILITIES

For reasons of function and curtailment of construction cost, multi-story sewage treatment facilities in Osaka City employ a structure in which the upper and lower layers are hydraulically unified, with no hydraulic pressure occurring on the intermediate slab between the layers. Operation of both layers must be stopped simultaneously when drainage is required during maintenance or repair. Accordingly, in a sewage treatment plant with fewer tanks, water load on other tanks increases. For an aeration tank vertically unified with a final settling tank, as well, both tanks must be stopped simultaneously. It is advisable, therefore, that multi-story facilities be introduced into plants with relatively large treatment capacity and many tanks. Water distribution to the upper and lower layers of multi-story settling tanks is not controlled on the inlet side but on the outlet side. Sludge in each layer is gathered by a chain-flight type sludge collector, with sludge on the upper layer falling onto the sludge hopper of the lower layer and being extracted together with the lower layer sludge. Fig. 1 is a diagram of the principle of two-story settling tanks.

- Two-story primary settling tank

- Two-story final settling tank (Telescopic outlet pipe in lower layer)

- Two-story final settling tank (Collective outlet pipe in lower layer)

Fig. 1. Principle diagram of two-story settling tank.
Multi-story sewage treatment facilities

Two-story Primary Settling Tank

Compared with the final settling tank, the primary settling tank contains low quality treated water and receives small influence from density current; thus, no considerable effect is expected to be exerted on total treatment efficiency even if outlet devices are gathered at the tank outlet end. Therefore, outlet troughs with V-notch weirs are used for both the upper and lower layers. No outlet pipe is used for the primary settling tank as there is a danger of clogging by floating solids and scum.

Uniform water distribution to the upper and lower layers is ensured by making the height of the V-notch weirs on the outlet side uniform. Sludge collected in the lower hopper is intermittently extracted by a pump shared by several tanks. Scum generated in the lower layer is taken up by a sludge collector along the lower face of the intermediate slab in the downstream direction, and is gathered by a scum collector installed just upstream of the outlet trough. The same basic structures are used at ten sewage treatment plants in the city.

Two-story Final Settling Tank

Two-story final settling tanks, currently in operation at eight sewage treatment plants, are classified mainly into three types of systems by outlet device type. All of these systems are of the same basic structure except for their outlet mechanism.

As the final settling tanks are important solid-liquid separation equipment that have a direct influence on final effluent quality, careful consideration must be given in designing effluent outlet devices. Since final settling tanks are susceptible to the effects of density current, concentrating all outlet troughs at the downstream end, as in the primary settling tanks, seems to be dangerous in maintaining stable effluent quality. Conventionally, outlet devices of the final settling tanks are distributed over the entire tank except at the inlet portion. For these reasons, outlet pipes, which can be arranged over a wide area in the same manner as for the conventional effluent troughs in the single-story final settling tanks, are used as outlet devices for the lower layer.

Sludge collected in the lower layer hopper is extracted to the sludge outlet channel by using the difference in water level. At the top of this sludge extraction device is a height-adjustable telescopic pipe. Due to its simple structure, this device has been conventionally used for the final settling tanks. To ensure reliable sludge extraction, air lift effects produced by supplying air into the pipe are also used together with the water level difference.

The initially developed outlet device is based on the system in which the upper layer uses the general V-notch weirs and troughs, with each outlet pipe in the lower layer connected vertically with the upper layer outlet channels. At the outlet pipe end, a telescopic pipe is installed to adjust height. This system is called the telescopic outlet pipe system. Two-story final settling tanks using this system are the most widely used and have been constructed at five sewage treatment plants in the city. However, as this system places restrictions on the use of the upper layer, a new system in which a collective pipe is installed to collect effluent from each branch has been developed. This is called the collective outlet pipe system.

Actual facilities that use this system have been constructed only at one plant. However, the development of the collective pipe system has eliminated restrictions on the use of the upper layer, permitting vertical combination with an aeration tank and construction of three-story final settling tanks. An idea of controlling flow at one point on the outlet side has been developed into the flow control system for three-story final settling tanks.

When the upper and lower layer outlet devices have different hydraulic characteristics, it becomes difficult to maintain uniform water flow in both layers if flow rate varies. Therefore, facilities using the outlet pipe system for both the upper and lower layers have been constructed at one plant. In this system, water level variation caused by flow rate change is larger than that when V-notch weirs are used.

Vertical Unification of Aeration Tank and Final Settling Tank

To vertically unify an aeration tank and final settling tank, treatment capacity per unit area for both tanks must be almost equal. Aeration tank depth, therefore, is determined by the design standards of both tanks.
Aeration tank water depth \( h \) (m) is expressed by aeration time \( T \) (hr.) and surface loading of final settling tank \( OFR \) (m\(^3\)/m\(^2\)/day) as follows:

\[
h = \frac{T \cdot OFR}{24}
\]

Water depth is set at approximately 6 m in accordance with the city's design standards.

The structural diagram is shown in Fig. 2. Sewage flowing into the aeration tank from one end of the structure returns to a place near the original point through the tank, flows into four lower layer final settling tanks via distribution chamber, and overflows into an effluent channel via outlet pipes. Equal distribution from the aeration tank into the four final settling tanks is attained by keeping overflow weir height at the final settling tank outlet uniform. Facilities based on this system have been constructed at two sewage treatment plants.

**Three-story Final Settling Tank**

As operation of two-story final settling tanks was found to be satisfactory, the city's multi-story facility program has been further promoted to construction of three-story final settling tanks. The three-story final settling tank has been made feasible by combining existing technologies including collective outlet pipes, the method of adjusting effluent rate by movable weir, and a final settling tank installed below an aeration tank. At present, these three-story facilities are in operation at three treatment plants.

The structural diagram is shown in Fig. 3. Flow in the upper, intermediate and lower layers is controlled by an overflow gate installed at each layer's collective pipe end. An alternative method is also available in which a butterfly valve is installed at the outlet pipe end to control flow. However, the city has adopted the overflow gate control method explained above as it permits visual monitoring of flow rate and water quality in each layer.

To extract sludge out of the hopper, two systems are used: the telescopic method using both water level difference and air lift effects and the method of directly extracting sludge from each hopper by pumping. Fig. 3 shows the direct extraction method using pumping. Generally, the latter method is more reliable and easier in controlling extraction volume than the former, but has a drawback in that many pumps are required to extract sludge. However, the pump requirements of the three-story tank, in which sludge from the three layers is collected into a hopper, are about one-third that of the one-story facilities. Not only three-story but multi-story final settling tanks employ multi-story chlorination tank structures to enhance land utilization efficiency.
For the same purposes, efforts have been made to further deepen aeration tanks; tank depth has been increased gradually from the initial 4.5 m to the present 10 m, almost equal to the depth of three-story final settling tanks.

![Diagram of three-story final settling tank](https://iwaponline.com/wst/article-pdf/23/10-12/1733/101406/1733.pdf)

**Fig. 3. Three-story final settling tank.**

**DESIGN OF COLLECTIVE OUTLET PIPES**

In designing collective outlet pipes for final settling tanks and other facilities, consideration must be given to uniform flow into each branch outlet pipe. This is important because irregular flow, if occurring, causes an increase in upflow rate at a portion of the tank and may result in re-floating and discharge of settled sludge.

Therefore, the collective outlet pipe must be designed such that the opening area becomes larger gradually from downstream to upstream. To this purpose, a formula expressing the outlet pipe opening area ratio which ensures uniform inflow has been developed based on Sueishi's (1959) "On the hydraulic design of perforated-lateral underdrain system." This formula and actual examples of application are introduced in this section. In developing the formula, a large number of holes provided in the pipe have been substituted by a continuous slit, with Bernoulli's equation used for the inflow from the slit and an equation of continuity and an equation of momentum for flow inside the pipe.

For outlet pipes in which branches are installed at uniform intervals, as shown in Fig. 4, when inflow volume \( q_L \) per unit branch length is constant, opening area ratio \( \beta \) at a given point of the outlet pipe is expressed as follows:

\[
\frac{1}{\beta^2} = -\frac{a}{a^2 + \frac{C_p}{C_L^2}} + \frac{Y_m}{U_m^2/2g} + 2 \left( 1 - \frac{M_L^2}{M_M^2} \right) + \frac{N_M}{N_L} \left( 1 - \frac{M_L^2}{M_M^2} \right)
\]

\[
\frac{1}{\beta^2} = -\frac{a}{a^2 + \frac{C_p}{C_L^2}} + \frac{Y_m}{U_m^2/2g} + 2 \left( 1 - \frac{M_L^2}{M_M^2} \right) + N_M \left( 1 - \frac{M_L^2}{M_M^2} \right)
\]

\( a = m^2 A_L / (S_L A_M) \): Ratio of total of branch opening area to main pipe section area

\( \beta = C_p \frac{A_p}{A_M} \): Dimensionless quantity showing ratio of perforation area to branch section area \( (C_p = 0.6 \sim 0.8) \)

\( N_L = 2g \frac{\eta_{L}^2}{L(3)^{1/3}} \): Dimensionless quantity showing friction loss head of a branch

\( N_M = 2g \frac{\eta_{M}^2}{M(3)^{1/3}} \): Dimensionless quantity showing friction loss head of the main pipe

\( A_p, S_p, C_p \): Area, pitch and discharge coefficient of perforation, respectively

\( A_M, S_M, C_M \): Area, pitch and discharge coefficient of branch section, respectively

\( N_M \): Main pipe section area

\( U_m, Y_m \): Flow rate at \( M = m \) inside the main pipe

\( \eta_{L, M} \): Manning coefficient for branches and the main pipe

\( R_L, R_M \): Hydraulic radius of branches and the main pipe

\( \beta \): Gravitational acceleration

The coordinates system and signs, \( L, \ell, M, m \) used in the present study are shown in Fig. 4.
In this equation, $\beta$ at any point can be obtained when the dimensions of the outlet pipe and its total loss head ratio $Y_m/(U_m^2/2g)$ are determined. With $\beta$ determined, when either perforation pitch or its area is given in the $S$ definition equation, the other is also determined.

With equation (2) alone, however, calculation must be repeated to obtain pitch and section area of branch pipes suitable and effective for design. To minimize the range of $S$ such that no practical problem arises, thus permitting streamlined design, an equation expressing the relation between max-min flow ratio $R_w$, $N_L$, $N_M$, $Y_m/(U_m^2/2g)$ and $\beta$ when branch pitch ($S_L$) and $\beta$ are uniform (is constant, $\beta$) is expressed approximately as follows:

$$\frac{S_n}{Y_m} = \frac{1}{2} \sqrt{\left(\frac{R_w^2 - 1}{(2 + N_M)} - 4 \frac{2 + N_L}{2 + N_M} \beta^2 \right)} = \frac{\frac{1 + R_w}{R_w}}{2 \sqrt{(2 + N_M)} + \frac{1}{\alpha^2} (2 + N_L)}$$

(3)

$\gamma = (C_p \cdot A_p)/(S_L \cdot S_p)$: Ratio of effective perforation area to water collection area

$R_w = q_L \max./q_L \min.$: ratio of the maximum to the minimum inflow ($q_L$) per unit branch length

$\beta$: Representative $\beta$ value, $\beta = 1/2 (\beta_{\max} + \beta_{\min})$ is used in the present study

The actual design examples of J. Sewage Treatment Plant are cited below.

Treatment capacity per tank in J. Plant is approximately 3,900 m$^3$/day (maximum daily flow). If installation area for clarified water extracting equipment is set within the range of two-thirds from the downstream side of the final settling tank, then $m = 18.5$ m and $\alpha = 3.1$ m.

Diameter of the outlet main pipe has been set at 500 mm, that of the branch at 200 mm, and the number of branches at nine, the same quantity as V-notch troughs for the upper layer.

Total perforation opening area ratio $\overline{\beta}$ should be minimized to draw $R_w$ as close to 1 as possible. Perforation diameter has been set at 40 mm so that no clogging may occur. Average perforation pitch $S_p$ has been set at 200 mm, about five times as large as diameter.

Thus, it has been concluded that $\overline{\beta} = 0.434$

Thus, from equation (3), the following are derived: $R_w = 1.8$ and $-Y_m/(U_m^2/2g) = 5.5$.

Thus $R_w$ is maintained at around 1.8 if holes of 40 mm diameter are arranged uniformly with 200 mm pitch. To attain further uniform inflow, however, $-Y_m/(U_m^2/2g)$ determined above is used to obtain $\beta$ at each point from equation (2). With perforation area $A_p$ set at 40 mm, perforation pitch $S_p$ was determined. $S_p$ obtained is shown in Table 1.

Perforation pitch for each branch is determined uniform, as the influence on treated effluent quality of partial irregularity of inflow in each branch, if occurring, is negligible.
TABLE 1  Example of Branch Perforation Pitch  

<table>
<thead>
<tr>
<th>Branch No.</th>
<th>L/ℓ</th>
<th>0.8</th>
<th>0.6</th>
<th>0.4</th>
<th>0.2</th>
<th>Average Perforation Pitch</th>
<th>Number of Perforations per Branch 3.1 m long</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1/18</td>
<td>180</td>
<td>166</td>
<td>156</td>
<td>150</td>
<td>165</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>3/18</td>
<td>182</td>
<td>169</td>
<td>159</td>
<td>150</td>
<td>168</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>5/18</td>
<td>186</td>
<td>173</td>
<td>164</td>
<td>158</td>
<td>172</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>7/18</td>
<td>193</td>
<td>180</td>
<td>171</td>
<td>166</td>
<td>180</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>9/18</td>
<td>202</td>
<td>190</td>
<td>181</td>
<td>176</td>
<td>189</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>11/18</td>
<td>212</td>
<td>201</td>
<td>193</td>
<td>189</td>
<td>201</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>13/18</td>
<td>224</td>
<td>214</td>
<td>206</td>
<td>202</td>
<td>213</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>15/18</td>
<td>238</td>
<td>228</td>
<td>221</td>
<td>217</td>
<td>228</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>17/18</td>
<td>254</td>
<td>244</td>
<td>238</td>
<td>234</td>
<td>244</td>
<td>13</td>
</tr>
</tbody>
</table>

Hydraulic Characteristics of Two-story Final Settling Tank Using Different Outlet Devices

Flow variation when outlet devices with different hydraulic characteristics are used for the upper and lower layers of a two-story final settling tank can be determined as follows:

\[
\Delta h = h_w - h_w^o = (h_p + h_c) - (h_w^o + h_c) \tag{4}
\]

hw: Overflow depth from the upper layer V-notch weir
hp: Difference between the upper layer V-notch overflow water level and the lower layer outlet pipe overflow water level
hc: Overflow depth from the lower layer outlet pipe

where values with a small zero indicate the standard values.

With \( N_U \) and \( N_L \) as the flow ratio of each layer to the standard value, the following equation is introduced by considering the hydraulic characteristics of the V-notch weir and pipe (\( h_w = Q^{2/5}, h_p = Q^2, h_c = Q^{4/3} \)):

\[
(N_U)^{2/5-1} = h_p/h_w^o(N_L^{2/3-1}) + h_c/h_w^o(N_L^{2/3-1}) \tag{5}
\]

\( N_U \): Ratio of upper layer flow rate to standard value
\( N_L \): Ratio of lower layer flow rate to standard value
where $w_2$, $h_{po}$ and $h_{co}$ are determined by design devices. Flow variation in the upper and lower layers can thus be found by the above equation.

Examples of flow variation for collective and telescopic type outlet pipes are shown in Fig. 6. As indicated in this figure, when a V-notch weir is used for the upper layer and outlet pipe for the lower layer, flow variation in the upper layer is larger than that in the lower layer. Also found in the figure is that flow difference between the layers for the telescopic system is smaller than that for the collective pipe system.

![Flow variation in the upper and lower layers of two-story final settling tank.](image)

**Fig. 6.** Flow variation in the upper and lower layers of two-story final settling tank.

**OPERATION CONDITIONS OF ACTUAL FACILITIES**

Osaka City has run multi-story sewage treatment facilities for over twenty years. Even the latest three-story final settling tanks have already been in operation for ten years.

Judging from the data obtained thus far through operation, multi-story facilities are not inferior in treatment performance to one-story facilities, and no maintenance and control problem is expected to arise from multi-story structures.

Annual average values of operation performance of various multi-story facilities are shown in Table 2. Load at A* and C* plants are slightly higher than the designed standard values, while the other three plants are operated at a load lower than the designed values. It can thus be concluded that operation conditions for each plant are satisfactory.
**TABLE 2 Sewage Treatment Performance of Multi-story Facilities (Average for 1987)**

<table>
<thead>
<tr>
<th>Items</th>
<th>Water Quality</th>
<th>Operation Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary Settling Tank Inlet</td>
<td>Primary Settling Tank Outlet</td>
</tr>
<tr>
<td></td>
<td>SS (mg/l)</td>
<td>BOD (mg/l)</td>
</tr>
<tr>
<td>A *</td>
<td>250</td>
<td>190</td>
</tr>
<tr>
<td>A' *</td>
<td>190</td>
<td>160</td>
</tr>
<tr>
<td>B</td>
<td>93</td>
<td>140</td>
</tr>
<tr>
<td>C *</td>
<td>310</td>
<td>170</td>
</tr>
<tr>
<td>C</td>
<td>110</td>
<td>120</td>
</tr>
</tbody>
</table>

* Sidestreams from sludge treatment facilities are included in primary settling tank inflow.

- All primary settling tanks are two-story structures except one-story A'.
- A and A': Three-story final settling tank with aeration tank 9~10 m in depth
- B: Aeration tank vertically combined with final settling tank
- C: Two-story final settling tank with aeration tank 6 m in depth

**EFFECTS OF DEVELOPMENT OF MULTI-STORY FACILITIES**

Introduction of multi-story settling tanks and deep aeration tanks is aimed at enhancing land utilization efficiency. To quantitatively determine their effects, sewage treatment facility structure occupancy area per unit treatment capacity in Osaka is shown in Table 3. This occupancy area includes that for inlet/outlet channels and other structures unified with the sewage treatment facilities, but does not include machinery buildings. It is not possible to reduce the occupancy area of two-story facilities to half of one-story structures as there are incidental inlet and outlet facilities. Calculated using the values in the table, conventional water treatment facilities comprising a single-story primary settling tank, a 4.5 m deep aeration tank and a single-story final settling tank, require 164 m² of land area per thousand m³ per day of treatment capacity, while the combination of a two-story primary settling tank, a 10 m deep aeration tank and a three-story final settling tank, currently considered standard in Osaka City, requires only 76 m², or 46% of the conventional occupancy area.

**TABLE 3 Area Occupied by Sewage Treatment Facility Structure**

<table>
<thead>
<tr>
<th>Items</th>
<th>Structure Occupancy Area (m²) per Treatment Capacity (thousand m³/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary settling tank</td>
<td>One-story</td>
</tr>
<tr>
<td></td>
<td>Two-story</td>
</tr>
<tr>
<td>Aeration tank</td>
<td>Water depth 4.5 m</td>
</tr>
<tr>
<td></td>
<td>6.0 m</td>
</tr>
<tr>
<td></td>
<td>10.0 m</td>
</tr>
<tr>
<td>Final settling tank</td>
<td>One-story</td>
</tr>
<tr>
<td></td>
<td>Two-story</td>
</tr>
<tr>
<td></td>
<td>Three-story</td>
</tr>
</tbody>
</table>

For sewage treatment facilities with treatment capacity of 200,000 m³/day, construction cost is compared between the one-story type and the standard multi-story type in Table 4. Construction cost differs by structure, with no considerable difference present in machinery and electricity equipment cost when comparing one-story structure with multi-story structures. Therefore, the table shows the results of calculation based on the same design standards for structures.
TABLE 4 Comparison of Construction Cost between the Multi-story and One-story Types
(Structure Cost of Facilities with a Treatment Capacity of 200,000 m³/Day)

<table>
<thead>
<tr>
<th>Items</th>
<th>Multi-story structure</th>
<th>One-story structure</th>
<th>Total Construction Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Structure (including Foundation Piles)</td>
<td>3,340</td>
<td>4,180</td>
<td></td>
</tr>
<tr>
<td>Retaining Wall and Earthwork (including Installation of Temporary Staging)</td>
<td>1,110</td>
<td>420</td>
<td></td>
</tr>
<tr>
<td>Total Construction Cost</td>
<td>4,450</td>
<td>4,600</td>
<td></td>
</tr>
</tbody>
</table>

The design standards used in this calculation, those currently in force in Osaka City, are shown in Table 5. As Table 4 indicates, multi-story facilities are lower than the one-story type in main structure construction cost, but are higher in retaining wall and earthwork expenses; thus the overall construction cost is almost equal for both types of facilities.

TABLE 5 Sewage Treatment Facility Design Standards (Osaka City)

<table>
<thead>
<tr>
<th>Items</th>
<th>Standard Values (Daily Maximum Flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary settling tank</td>
<td>Surface loading 40 m³/m²·day</td>
</tr>
<tr>
<td></td>
<td>Effective water depth 3.0 m</td>
</tr>
<tr>
<td>Aeration tank</td>
<td>Aeration time 6.5 hours</td>
</tr>
<tr>
<td>Final settling tank</td>
<td>Surface loading 23 m³/m²·day</td>
</tr>
<tr>
<td></td>
<td>Effective water depth 3.0 m</td>
</tr>
</tbody>
</table>

SUMMARY

Due to rising land prices and advanced urbanization, enlargement of sewage treatment sites in Osaka is extremely difficult. To enhance land utilization, therefore, construction of multi-story facilities has been promoted in the city. The city's multi-story sewage treatment facilities are characterized by the use of outlet pipes for the final settling tanks. To optimize the effects of these outlet pipes, streamlined design methods have been developed. Structure occupancy area per unit treatment capacity for multi-story facilities can be reduced to 46% that of the conventional one-story type.

REFERENCE