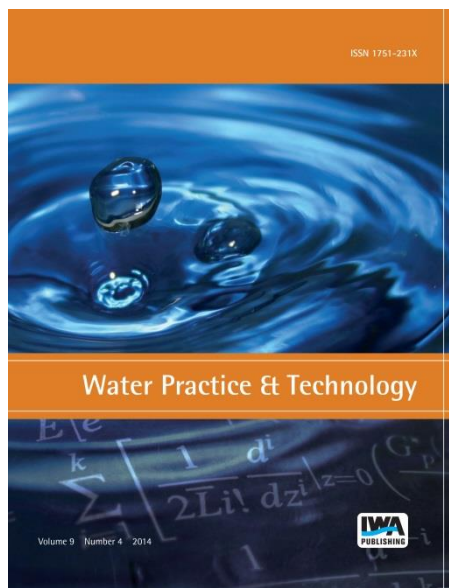


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A new approach for studying the operation of a secondary sedimentation tank

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Abstract

A new theory regarding the behavior of activated sludge in a sedimentation tank has been developed, based on the principles of momentum preservation in suspended sludge, the ratio between drag and gravity, and the potential energy of the sludge blanket. Field tests enabled the determination of new criteria for the functioning of secondary sedimentation tanks complying with this new theory.

Key words: secondary sedimentation tank, solid flux theory, sludge momentum, sludge blanket potential energy

A NEW APPROACH TO UNDERSTANDING SSTs

Currently, the solid flux theory is the only one widely accepted as explaining the way in which secondary sedimentation tanks (SSTs) function, despite its gross simplifications. For example, it is hard to believe that sludge drawn from the center-bottom of the tank causes downward solid flux descent at the same velocity across the SST's surface. Even harder to defend is the hypothesis that the sludge particle sedimentation rate remains the same in both dynamic and static conditions, ignoring the turbulent diffusion caused by hydrodynamic stresses in the liquid mass. In fact, if the horizontal gradient concentration is not taken into account (contrary to the solid flux theory hypothesis), it becomes impossible to explain SST performance.

To improve understanding of SST functioning, the behavior of an operational SST must be analyzed. This has been done by various researchers (Bertola 1980; Boyle 1981), particularly with regard to the sludge blanket characteristics (considering both the horizontal and vertical concentration gradients), as well as the hydrodynamic fields within the SST. These findings can then be interpreted on the basis of hydrodynamic principles:

- Momentum preservation, in the absence of energy loss;
- Fluid (thickened sludge) motion from relatively higher to lower potential energy areas;
- Ratio between inertia and gravitational forces.

The potential energy per square meter at any given point in the SST is given by:

$$E_p = (G_s - G_l)/G_s \int_0^H C(h) \times h \times dh \quad (1)$$

where G_s = specific gravity of solid particles; G_l = specific gravity of clarified water; G_s & G_l given in any homogeneous units; $C(h)$ = sludge concentration at a specific height (h) from the bottom; (Kg/m^3); h = height above the bottom of the SST; (m); H = height of the SST. (m); $E_p = (\text{Kg} \times \text{m})/\text{mq}$.

The energy present, should its loss arising from fluid flow be negligible, can be converted into different forms, but its absolute value will not increase or decrease.

Experiments to determine the sludge blanket characteristics at the bottom of the SST were performed on three SSTs (Appendix 1), the first with a rectangular shape (Castel Giubileo WWTP, Rome, Italy) and the other two circular (Bracciano and Avellino WWTPs, central Italy). As the results from the circular SSTs were similar, only Bracciano will be referenced below, for convenience. The SSTs' dimensions and operating conditions are indicated in Figure 1 (all dimensions are in meters).

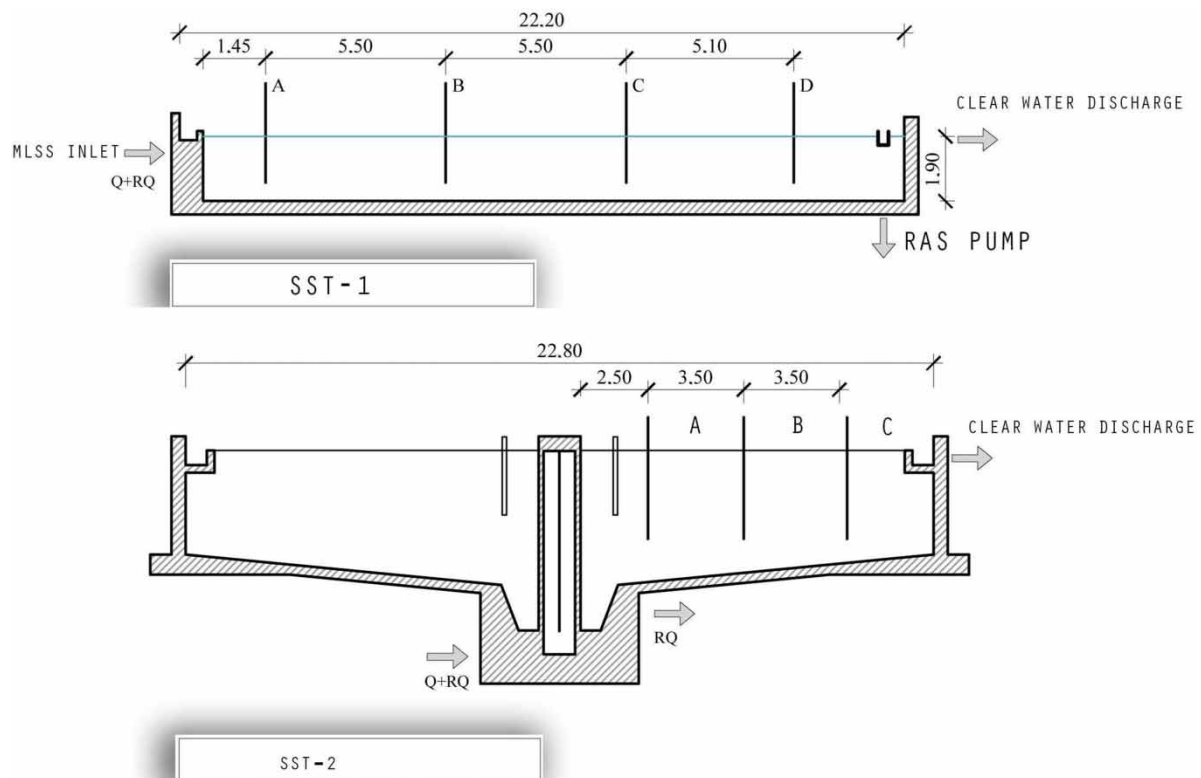


Figure 1 | Sections of the two SSTs showing the vertical lines on which samples were taken.

Of these two tanks:

- The first, SST-1, is rectangular, with a flat bottom and horizontal flux; it has a pump for Recirculated Activated Sludge (RAS) suction at the bottom, near the outlet weir;
- SST-2, is circular, with radial flux in normal operation.

The main difference between the two SSTs is that the thickened sludge and clarified water move in the same direction in SST-1, but in opposite directions in SST-2. In the latter, the clarified water moves outwards (centrifugally) and the thickened sludge inward (centripetally), in common with all circular SSTs. Sludge samples were taken at different heights on three vertical lines at different distances from the Mixed Liquor Activated Sludge (MLSS) inflow point, from both SSTs. The results are shown in Figures 2 and 3 (both Castel Giubileo) and 4 (Bracciano), where the X-axis scale (concentration) is logarithmic. The Y-axis (sampling distance above the bottom) is linear. The bottom of SST-2 is inclined, so depth measurements were taken in the deepest section of the tank, i.e. the section closest to the center.

The forms of these curves enable some deductions to be made:

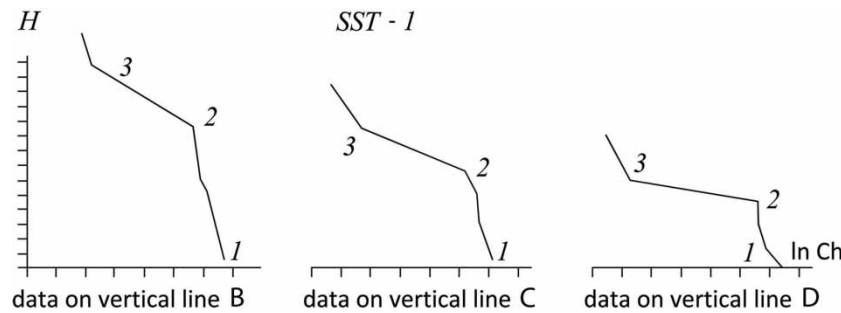


Figure 2 | 'Chair-shape' diagrams moving from the inlet (left) to outlet (right) of the tank.

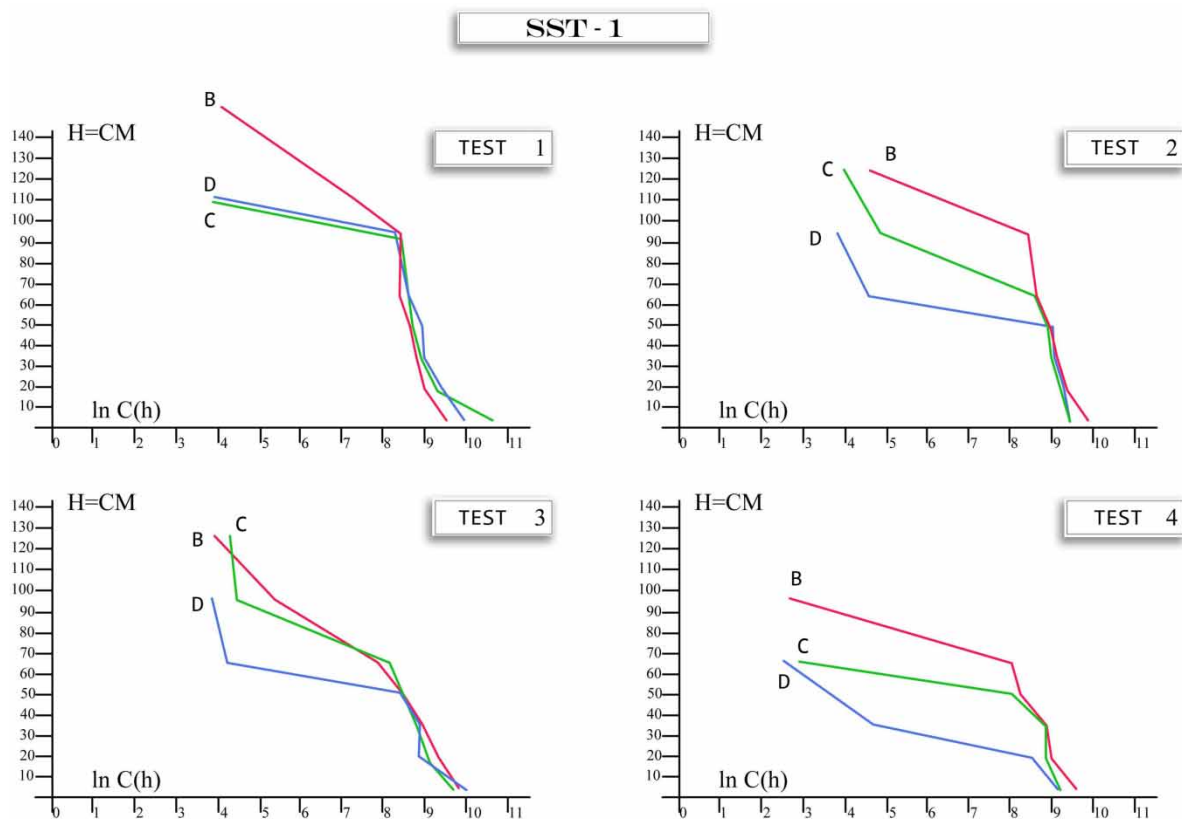


Figure 3 | The overlapping lines – B, C and D – in each portion of the figure represent the transition of fluid from the tank's inlet to its outlet.

SST-1 (horizontal flux, RAS suction closest to the outlet weir for clarified water)

Figure 2 clearly shows the chair-shape of lines B, C and D, with a sub-vertical lower part (concentration levels almost constant with depth); a central part with a steep slope (rapid concentration increase with decreasing depth) and an upper part with another sub-vertical slope. Data from point A were ignored because of its proximity to the inlet weir. Using static, lab sedimentation tests as a basis for explanation:

- The lower part – the chair leg – represents the thickened sludge, its solids concentration increasing much more slowly than that of the sludge in the sedimentation phase; the average sludge concentration is greater than that of the influent MLSS;
- The central part – the seat – represents the sludge during sedimentation; the average concentration in this layer is less than that in the incoming influent MLSS;

- The upper part – the back – represents clarified water. (The upper part is missing when only a single sample of clarified water was taken.)

The three vertical curves overlap at first, separating only in the upper sections, where the sludge concentration at any height increases with decreasing distance from the MLSS inlet

In Figures 2 and 3 the diagrams on the three vertical lines represent the transition of MLSS from the inlet towards the outlet. In this movement the central part in the curve tends to become horizontal, i.e., close to the weir outlet there is only thickened sludge, above which is only clarified water. Analysis of the data appears to show that the potential energy of the sludge blanket decreases as it moves from the MLSS inlet towards the RAS suction point. Thus, going in the same direction, at the same height above the tank bottom, its concentration decreases. The presence of a sludge blanket, even at the MLSS inlet, is caused by the creation of a density current at the bottom.

SST-2 (circular tank with radial flux, the lower portion of the sludge blanket moving centripetally and the clarified water centrifugally)

The curve in Figure 4 also exhibits a sub-vertical lower part with low concentration variations, and a lower slope central part that identifies higher concentration variations. The semi-vertical section does not appear on the vertical axis closest to the tank's center because of turbulent diffusion. This is greater than in SST-1 as the two liquids (influent MLSS and thickened sludge) move in opposite directions centripetally and centrifugally, with maximum speed near the decanter center. The curves show:

- A lower layer with a semi-vertical slope, representing thickened sludge;
- An upper layer with a much shallower slope, representing the sludge in the decantation phase.

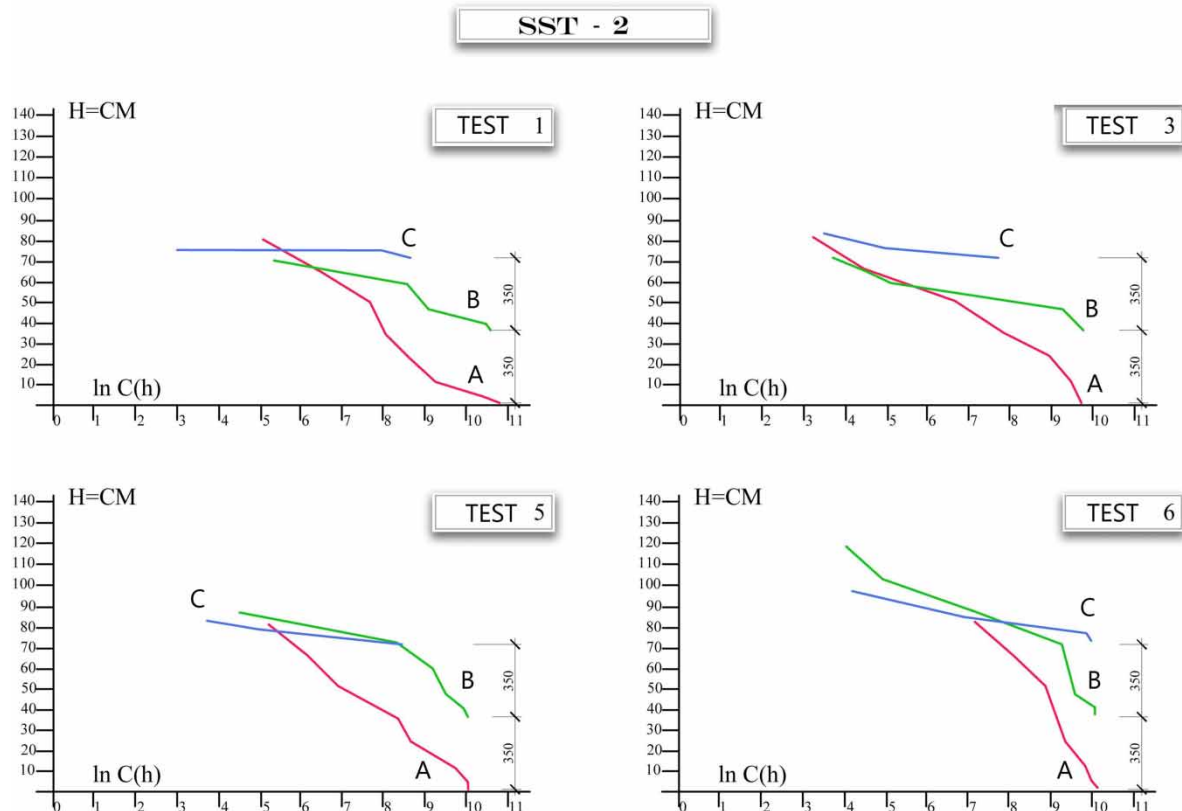


Figure 4 | The overlapping lines – A, B and C – in each portion of the figure represent the transition of fluid from the tank's inlet to its outlet.

The upper layer tends to disappear in transit from the MLSS inlet to the outlet weir. In other words, clarified liquid sits on top of the (thickened) sludge, in the same way as observed in SST-1. Convergence of the three curves in the upper part of the diagram shows that the clarified water/sludge blanket interface is horizontal throughout the tank. As in SST-1, the sludge concentration is lower towards the RAS suction point, at the same depth, and the sludge blanket's potential energy decreases as it moves towards the RAS suction.

The data obtained on the vertical line near the center of SST-2 have been further elaborated. If a Cartesian plane is drawn, and the log-concentrations are put onto the x axis with the squares of the heights on the y axis, the results tend to line up. Therefore the sludge concentration, related to height, is given by a semi -Gaussian function with the maximum value at the bottom – Figure 5.

Thus:

$$C(h) = C_{\max} \times e^{(-0.5(h/S)^2)} \quad (2)$$

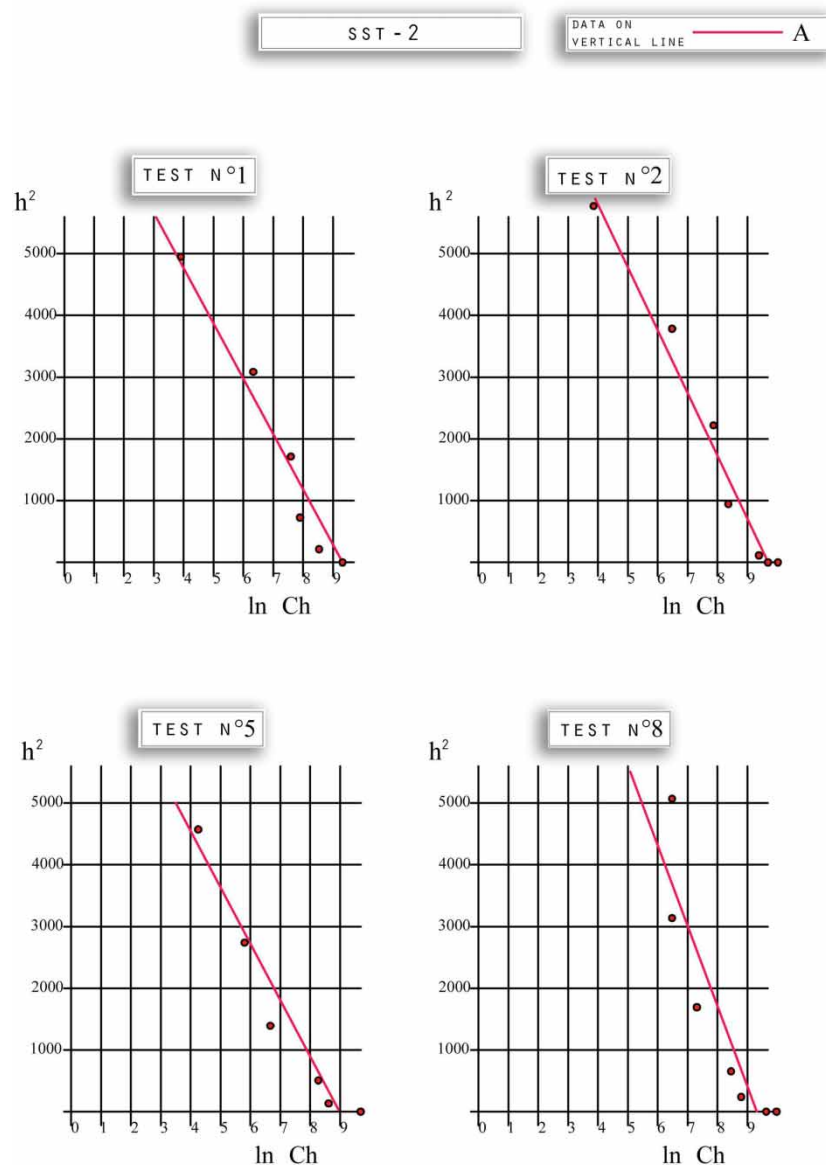


Figure 5 | Log-concentration vs the square of the height, close the tank center, for different tests on SST-2.

where h is the height above the tank bottom (cm); $C(h)$ the sludge concentration at height h (mg/l); $C_{\max}$ is the maximum sludge concentration at the bottom of the tank (mg/l); S is the variance of the Gaussian function characterizing the sludge blanket at the point concerned: for very high values of S , the concentration varies very little with height and vice versa for a very low S . (cm).

This result is strong evidence that there is a single valid expression representing the sludge concentration, from the bottom to the top of the sludge blanket, with no discontinuity.

Equations (1) and (2) lead therefore to:

$$E_p = (G_s - G_l)/G_s \times C_{\max} \times S^2 \quad (3)$$

G_s and G_l are defined above.

THE HYDRODYNAMIC FIELD OF AN OPERATING SST INTERPRETED IN LIGHT OF THE SLUDGE BLANKET CHARACTERISTICS

There have been numerous studies of SST hydrodynamics based on mathematical models ([Lakehal et al. 1999](#); [Ekama & Marais 2004](#)), but relatively few based on direct measurements obtained in the field. The main drawback of hydrodynamic mathematical model studies is the supposition that the densities of the sludge and the clarified water are the same, so that sludge velocity and direction depend only on:

- sludge sedimentation velocity (as in a jar test);
- the equations for the conservation of particulate mass (in stationary conditions, the concentration of sludge everywhere in the tank remains constant, and there is no gain or loss of solid mass);
- the boundary conditions;
- the equations for conservation of water mass and momentum.

The conservation of sludge momentum is not taken into account. Because of this, the hydrodynamic field, measured directly in an operating SST and not as given by mathematical models, is considered below ([Vanrolleghem et al. 2006](#)). A typical hydrodynamic field inside an operating, circular SST is illustrated in [Figure 6](#) ([Bertola 1980](#)).

Several points are noted in relation to the real hydrodynamic situation, with small, but relevant, differences to those derived from mathematical models:

- The bottom flow, which is centripetal towards the RAS suction, comprises thickened sludge;
- The intermediate flow, immediately above the bottom flow, is centrifugal. Close to the tank's outer wall, the intermediate flow divides into two streams: one turning upward toward the outlet weir and the other downward, toward the thickened sludge. In this layer the significant change in sludge concentration at different depths is mitigated by turbulent diffusion, which increases as the velocities of the two layers increase. The thickened sludge moves towards the bottom center of the tank, the upper layer towards the outer vertical wall. Thus, in the central part of the tank, where the velocities of the two layers are high, no sedimentation can occur;
- The uppermost layer comprises clarified water and, close to the outlet weir, it divides into two streams, one going towards the outlet weir, the other generating a superficial stream which tends to return towards the center of the tank.

The prime issue affecting the performance of an SST is the way in which the intermediate stream divides into two, feeding both the bottom flow of thickened sludge and the upper stream of clarified water. Why does this layer divide into two and at what distance from the central feed does it happen? The answer is that, as long as the outer wall, where the outlet weir is, is far enough and the stream's velocity high enough, the stream moves centrifugally without difficulty, and with little or no sedimentation, hampered by

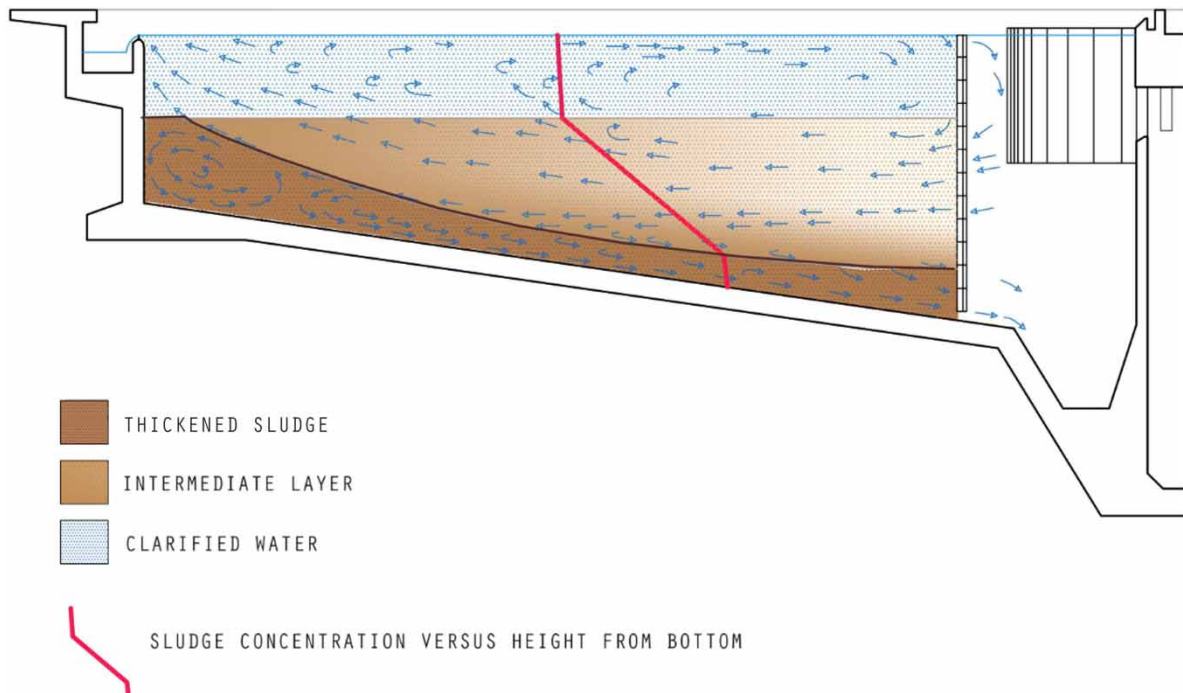


Figure 6 | The hydrodynamic field (represented by the arrows) and the sludge concentration in a circular SST.

turbulent diffusion. When the sludge stream gets close to the wall, however, and its velocity decreases because of the tank's circular shape, its horizontal velocity decreases. At this point, the ratio between the drag of the clarified water on the solid particles and those particles' inertia begins to have an effect:

- If the ratio is too high (excessive liquid velocity and poor sedimentation), the sludge particles will be dragged toward the outlet weir;
- If, instead, the ratio is low enough – i.e., the reverse of that above – the clarified water leads the velocity vectors upward, toward the outlet weir, but the solid particles, thanks to their greater inertia, continue horizontally to accumulate in the stockpile of thickened sludge beside the outer wall, in the 'dead zone' where all velocity vectors are very low.

If there is no loss of energy, the impact of the solid particles in the thickened sludge in the 'dead zone' raises the potential energy of the sludge blanket. The change is equal to the change in momentum of the solid mass arriving and can be quantified as:

$$E_p = K \times C \times (Q + rQ) \times (Q + rQ) = K \times C \times (Q + rQ)^2 \quad (4)$$

where K is a constant; (related to $(G_s - G_l)/G_s$ and the tank geometry); $C \times (Q + rQ)$ is the sludge mass entering the SST in unit time, defined as the 'horizontal solid flux'; $(Q + rQ)$ for a given SST – i.e., for an equal peripheral cylindrical surface – is proportional to the horizontal solid flux velocity, which pertains to the middle layer with centrifugal flow.

The stockpile of thickened sludge beside the outer wall is the source of the flow of thickened sludge to the RAS suction point. It acts as a fluid with its own dynamic characteristics, moving in the direction of decreasing potential energy. The RAS suction system does not draw directly from the sludge blanket when distances exceed twice the tank's depth. Its role is to reduce the sludge blanket's potential energy around the suction point, causing a density current of thickened sludge between the tank wall and its center at the bottom. When conditions in the tank are stable, the flow of thickened sludge towards the center balances the increase in potential energy, owing to the changes in momentum of the solid horizontal flux.

In a transitory phase, howsoever caused – e.g., by RAS flow reduction – the mass balance is not maintained and equilibrium is restored by a sequence of events:

- the mass of solids in the tank increases;
- the potential energy of the sludge blanket increases, as does its thickness;
- the average density of the return flow of thickened sludge increases; and,
- the mass equilibrium is restored, unless the system goes into crisis – i.e., sludge passes over the outlet weir.

It can be hypothesized from this that the potential energy of the sludge blanket at the tank wall is:

- directly proportional to the term: $C \times (Q + rQ)^2$;
- and inversely proportional to r , the ratio between flow from the RAS and Q , the influent flow.

That is:

$$E_p = K \times C/r \times (Q + rQ)^2 \quad (5)$$

where K is a constant which, for a given tank, depends solely on the sludge's sedimentation characteristics.

NEW CRITERIA FOR SST DESIGN

As noted, the dimensions essential for the correct functioning of an SST are the relationship between the drag of the sludge towards the outlet weir – i.e., its velocity close to the outlet – and the inertia of the sludge. The drag velocity towards the brink of the outlet is given by the ratio between the flow to be treated, Q (m^3/h), and the cylindrical surface of the layer being decanted (mq), just before it divides into two streams going in different directions. The cylindrical surface is not related to the total height of the tank but, as a first approximation, is proportional to it. It can be defined as V_1 and expressed as $\text{m}^3/\text{h}/\text{m}^2$.

As for the inertia of the sludge particles, an effort has been made to define a parameter that is easily determined in the field and could reflect the disposition of the sludge to settling. It needs to reflect not only the sludge's increased density relative to water but also the initial sludge concentration. A highly thickened sludge does not settle, despite being denser than water.

A parameter that appears to correspond to these requirements is the pure number defined as:

$$V_2 = \frac{1/\text{SVI} - C/1000}{C/1000} \quad (6)$$

where SVI is the Sludge Volume Index determined by traditional methods; and, C is the MLSS concentration (g/L).

$1/\text{SVI}$ is the apparent specific weight of decanted sludge. The term $C/1000$ represents the inverse of the SVI that the sludge would have if it had no inclination to settle, whether this depended on the low density of the sludge particles (equal to that of the water) or the fact that the sludge was already thickened.

The SVI, as determined by the usual procedures, is not always reliable in evaluating potential sludge settlement. In trying to move forward with research on secondary sedimentation efficiency, which might require a great deal of data, it has been necessary to make use of the standard form of SVI, however, even though it is not completely suitable. Measurements from operating sedimentation tanks (diameters 12–33 m) confirmed that SST efficiency was allowed only with values in the V_1/V_2 relationships below $5\text{--}6 \text{ m}^3/\text{h}/\text{m}^2$. These tests have been carried out systematically on WWTPs in Camaione, Massa and Carrara Municipalities (northern Tuscany region, Italy), and occasionally in >10 other WWTPs (Appendix 2).

Sporadic measurements taken on tanks with different types of outlet gave different values, but confirmed the importance of the V_1/V_2 relationship. It could be higher for equipment with more efficient outlet systems (e.g. Stamford baffles) and lower for those with less efficient outlets. Obviously, the fact that the values of the V_1/V_2 relationships are acceptable confirms that the separation of water from sludge is possible but does not guarantee SST functioning.

The other necessary condition is that all separated sludge is removed from the bottom of the tank and, thus, that there is sufficient differential in the potential energy of the sludge blanket between the outer wall and center of the tank.

Consequently, pinpointing the criteria to predetermine the height of the sludge blanket and its structure (variations between concentration and height) is equivalent to finding a criterion to check a decanter. The measures discussed indicate some correlation between the potential energy of the sludge blanket close to the tank center and the expression:

$$C/r \times (Q + rQ)^2 \quad (7)$$

which is the formula given above for potential energy at the tank's outer wall.

This could be explained by the strict correlation between the sludge blanket's potential energy at the center and that at the SST's margin/wall. The experimental result can be summarized as:

$$E_p = K \times C/r \times (Q + rQ)^2 \quad (8)$$

SST - 2 - DATA ON VERTICAL LINE A

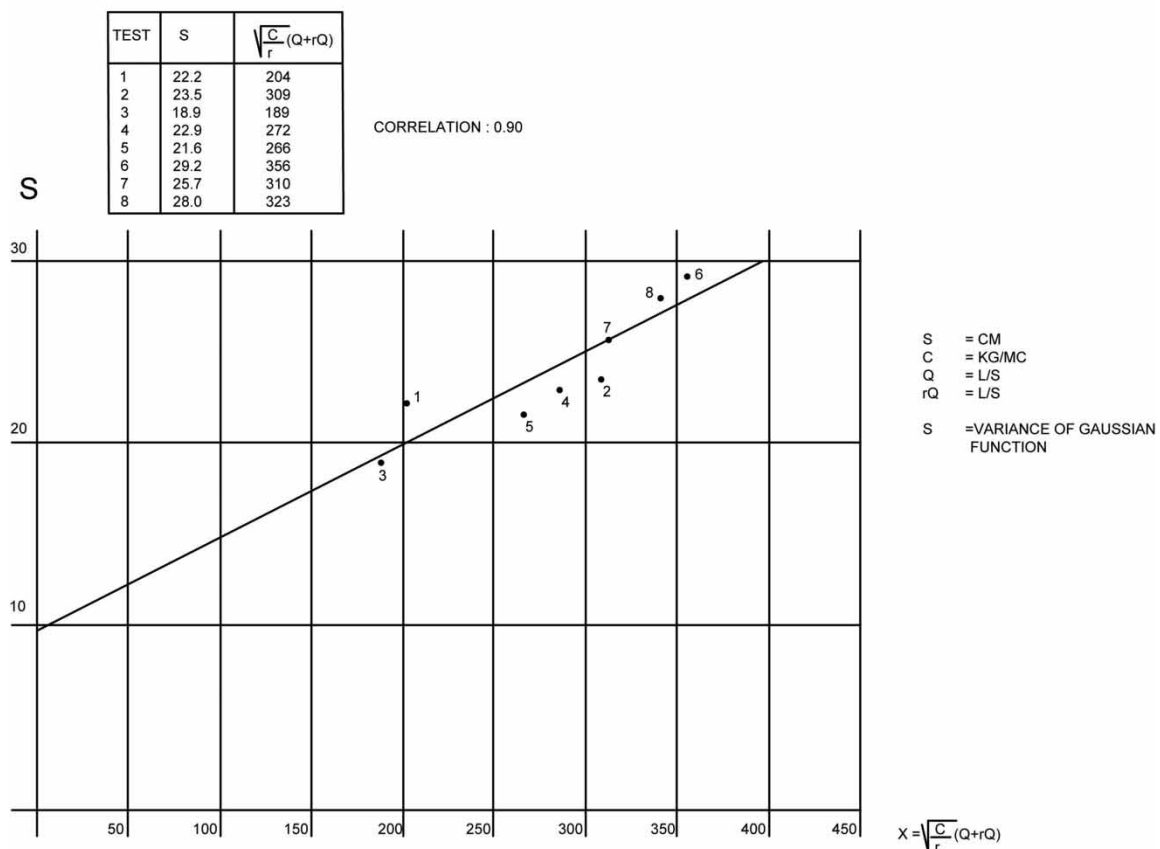


Figure 7 | Correlation between S^2 (S = variance of Gaussian Function, see formula 2) and the term $C/r \times (Q + rQ)^2$.

Equations (8) and (3) lead therefore to:

$$(G_s - G_l)/G_s \times C_{\max} \times S^2 = K \times C/r \times (Q + rQ)^2 \quad (9)$$

where $(G_s - G_l)/G_s$ and K are constants related to the tank geometry and sludge characteristics.

The tests carried out have confirmed formula (9) (Figure 7).

The importance of Equation (9) rests on the possibility of obtaining the different values of S as other parameter values change and, therefore, with Equation (2) calculating the extension and characteristics of the sludge blanket. It is noted that the minimum value for E_p in Equation (8), and hence the minimum sludge blanket level, is given for $r = 1$; in accordance with common experience.

CONCLUSIONS

A new approach has been developed for studying SST operation. This study covers the basic physical principles applying to suspended sludge in an SST – preservation of momentum, the ratio of drag to gravity, and the potential energy variations of the sludge blanket under changing hydrodynamic conditions. Tests carried out have demonstrated that the approach is correct, and that it is possible to define new design and verification criteria for SSTs.

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APPENDIX 1

The sludge blanket structure analysis (sludge concentration gradient under different operating conditions) was performed at various WWTPs between July and December 1993:

1. Castel Giubileo, Rome, Lazio region, Italy. (Rectangular SST)
2. Bracciano, Lazio region, Italy. (Circular SST)
3. Avellino Est, Campania region, Italy. (Circular SST)

The WWTPs operating conditions are as shown in Table AI:

Sludge samples were taken by stopping the sludge scraper, using a special sampler that enabled calibration of the depth of sampling. TSS analyses were done by a specialist laboratory.

It was clear quite early on that the results from the Bracciano and Avellino WWTPs were similar, and it was decided to continue only with Bracciano WWTP.

During the test period the operating characteristics of the remaining two SSTs changed as follows:
Castel Giubileo

- Clarified water flow: from 6.0 to 20.0 L/s

Table A1 | Operating conditions at the SSTs studied

	Castel Giubileo	Bracciano	Avellino
Population equivalent (pe)	12,500	34,000	35,000
Primary sedimentation	No	Yes	Yes
Average flow (L/s)	40	100	92.5
Denitrification	Yes	No	No
MLSS concentration (kg/m ³)	>3	>3	6
Organic load (kg-BOD ₅ /d/kg-MLSS)	<0.1	<0.25	<0.1
Operating units (number)	4	2	2
Length/diameter (m)	22	22.5	29.0
Width (m)	5.0		
Height (m)	1.9	1.8	2.0

- r (RAS ratio): 0.6 to 1.2

Bracciano

- Clarified water flow: from 26.5 to 47.5 L/s
- r (RAS ratio): 0.29 to 1.0

APPENDIX 2

Measurements from operating sedimentation tanks were taken during 2010. This was done systematically in the WWTPs at Camaiore, Massa and Carrara (northern Tuscany, Italy), and occasionally in >10 other WWTPs (mainly in Tuscany).

Observations were made of:

1. Clarified water flow
2. MLSS concentration
3. SVI in MLSS

The purpose of the analysis was to demonstrate the existence of a maximum V1/V2 ratio value above which the SST was in default. Because of this, the most interesting data came from SSTs that were not working properly or were in default, while those with low V1/V2 ratio values and performing well, produced data of less significance.

Table A2 shows the values collected from Camaiore WWTP, representing discontinuity in performance:

In the Ronciglione WWTP (Lazio region, Italy), which has a much less efficient SST outlet system, the default conditions (TSS > 50 ppm) occurred when V1/V2 ratio values were equal to or higher than 3.0 m/h.

Table A2 | Values from Camaiore WWTP representing performance discontinuity

V1 (m/h)	SVI (cc/gr)	V1/V2 (m/h)	TSS (ppm)
1.48	268	10.0	>35
1.48	246	5.1	30
1.48	152	4.8	22
1.48	95–169	0.9–4.8	<10