ASPECTS OF SETTLING IN THE ACTIVATED SLUDGE PROCESS

CHRISTOPHER M. BYE

B.Eng. Civil Engineering (McMaster University)

A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree

DOCTOR OF PHILOSOPHY

McMaster University

Department of Civil Engineering

ASPECTS OF SETTLING

For T...you are my sunshine...

DOCTOR OF PHILOSOPHY (2000) McMASTER UNIVERSITY
(Civil Engineering) Hamilton, Ontario

TITLE: Aspects of Settling in the Activated Sludge Process

AUTHOR: Christopher M. Bye, B.Eng. (McMaster University)

SUPERVISOR: Professor P.L. Dold

NUMBER OF PAGES: xv, 158

ABSTRACT

This study focuses on sludge settleability and SVI-type measures. Quantification of sludge settleability is crucial. This usually is done via empirical relationships. Parameters used in these relationships require measurement of sludge zone settling velocity in column settling tests over a wide range of concentrations. Due to the extensive experimental effort involved, several alternative measures (e.g. SVI, DSVI, SSVI) have gained favour for monitoring sludge settleability at full-scale treatment facilities. There is considerable debate over which SVI-type measure is best.

The study also includes a section on one-dimensional settling tank models. These models often are incorporated into wastewater treatment process simulators. Many of the one-dimensional settling tank models proposed to date are plagued by numerical instability and solution problems.

Background for this thesis is provided in Chapter 2. Included in this section is background on settling tests used to quantify the effect of suspended solids concentration on sludge settling velocity. Chapter 2 also provides background on the development of secondary settling tank modelling.

The main body of this thesis is presented as a series of four papers. The first paper (Chapter 3) addresses the considerable confusion which exists as to the best SVI-type parameter and experimental technique to use. A simple mechanistic model was developed and used to evaluate the effects of biosolids characteristics and test parameters on SVI-type indices. The model explains many of the artifacts associated with SVI and questions the validity of correlations for zone settling parameters based on SVI-type measures.

The second paper (Chapter 4) examines the approach of correlating SVI-type measures with zone settling velocity (ZSV) parameters for use in flux theory analysis (design or

operating charts). Correlations were assessed using the model developed in Chapter 3. The results show that use of the correlations may lead to erroneous results.

The third paper (Chapter 5) presents experimental data to demonstrate that differences in column height and sludge concentration can lead to large differences in calculated SVI for a given sludge. The model developed in Chapter 3 was used to further highlight these potential problems and evaluate the effects of sludge characteristics and test parameters on SVI-type indices. The paper raises considerable doubt regarding the validity of correlations for zone settling parameters based on SVI-type measures. An alternative SVI-based method was proposed for determining zone settling parameters.

The fourth paper (Chapter 6) outlines the approaches commonly used in one-dimensional layered secondary settling tank models. Two cases were examined: steady-state for a continuous flow secondary settling tank, and unsteady-state for a batch settling test. These cases were used as a basis to provide a rational explanation of numerical solution and stability problems that historically have plagued the one-dimensional layered modelling approach. The results show that the approach of introducing flux constraints into one-dimensional models should be avoided.

ACKNOWLEDGEMENTS

There are many people I would like to thank.

First of all, I would like to express my gratitude and deep appreciation to my friend and supervisor Peter Dold. He has had a tremendous positive effect on me, both personally and professionally. I feel fortunate to have had the opportunity to work with him, and even more so to have gained his friendship.

Gratitude also is due to my committee consisting of Dr. Dave Chapman, Dr. Rich Jones, and Dr. Brian Baetz. Their counsel throughout the process, whether it be related to courses, comprehensives, thesis, or personal matters, has been invaluable.

I also would like to express my appreciation to Debbie Smaluck and Gail Britton for all they have done for me (with endless patience!) over the years.

This work could not have been accomplished without the love and support of family and friends. It is difficult to articulate how much this has meant to me. Each of you has helped me through this journey in your own unique way, and for that I am eternally grateful. My parents, Lloyd and Gayle, and Tanya's parents Ray and Sue deserve special mention for their love and support.

Finally, I want to take this opportunity to thank my wife Tanya. Her boundless love, patience, and enthusiasm enabled me to make it to the end.

TABLE OF CONENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY OF TERMS AND SYMBOLS

SVI	Sludge Volume Index (as per *Standard Methods*) (mL/g)
DSVI	Diluted Sludge Volume Index (mL/g)
SSVI	Stirred Specific Volume Index (mL/g)
$SSVI_{3.5}$	Stirred Specific Volume Index @ 3.5 g/L (mL/g)
USVI	Sludge Volume Index performed without stirring (mL/g)
SSVI	Sludge Volume Index performed with stirring (as per *Standard Methods*) (mL/g)
ZSV	Zone Settling Velocity (also known as hindered or Type III settling velocity) (m/h)
SV_{30}	Sludge volume after 30 minutes (mL)
SV_0	Initial sludge volume (mL)
V_S	Sludge zone settling velocity (m/h)
V_0	Empirical Vesilind sludge settling velocity parameter representing sludge settling velocity at infinite dilution (m/h, m/d)
K	Empirical Vesilind sludge settling velocity parameter which quantifies the effect of sludge concentration on settling velocity (m^3/kg)
X	Mixed liquor total suspended solids concentration (g/L)
X_0	Initial suspended solids concentration in a column settling test, or clarifier feed concentration (g/L)
X_M	Maximum sludge concentration attainable under gravity compaction conditions (g/L)
H_0	Initial height of sludge in a column settling test (m)
H_{30}	Height of the column settling test sludge-water interface after 30 minutes (m)
H'	Final settled height in a column settling test (m)
t	Time (h)
t_F	Time for flocculation at the beginning of a column settling test (h)
t_{elbow}	Time in simulated column settling test when maximum compactability is reached
Qi	Influent flow rate (m^3/d)
A	Clarifier or settling test vessel surface area (m^2)
Qi/A	Clarifier surface overflow rate (m/h, m/d)
G	Solids flux through the clarifier area (kg/m^2/h)
G_L	Limiting solids flux through the clarifier area (kg/m^2/h)
G_{ap}	Applied solids flux through the clarifier area (kg/m^2/h)
s	Clarifier underflow recycle ratio
X_R	Clarifier underflow recycle solids concentration (mg/L, g/L)
R_C	Critical clarifier underflow recycle ratio (the maximum possible underflow recycle ratio within thickening criterion constraints)

X_i	Solids concentration in layer "i" of a one-dimensional settling tank model (g/L)
V_{UP}	Upflow velocity in one-dimensional layered settling tank model (m/d)
V_{DN}	Downflow velocity in one-dimensional layered settling tank model (m/d)
X_f	Feed solids concentration in one-dimensional layered settling tank model (g/L)
Δt	Time step in dynamic one-dimensional layered settling tank model (h)
Δz	The layer thickness in dynamic one-dimensional layered settling tank model (m)
m	The total number of layers used in dynamic one-dimensional layered settling tank model
i	The space index in dynamic one-dimensional layered settling tank model
n	The time index in dynamic one-dimensional layered settling tank model
Ω	Empirical correction factor used by Härtel and Pöppel (1992) and Otterpohl and Freund (1992) in dynamic one-dimensional layered settling tank model
X_t	Threshold concentration parameter used in Takács one-dimensional settler model (g/L)

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Settling is very important in the performance of suspended growth activated sludge systems. The secondary settler (shown in Figure 1.1) performs two critical functions in the wastewater treatment process. The first is to provide a clarified effluent in which suspended solids concentrations are kept to a minimum. Failure to perform this objective can result in effluent quality standards violations. The second function of the settler is to provide a thickened underflow for return to the biological reactor. Failure in this aspect of operation will cause a rising sludge blanket that may overflow the effluent launders, i.e. a gross settling failure. Under dynamic operating conditions a thickening failure situation may not persist (e.g. if influent flow rate decreases). Irrespective, difficulties in thickening may lead to a decreased solids mass in the biological process which will adversely affect its performance.

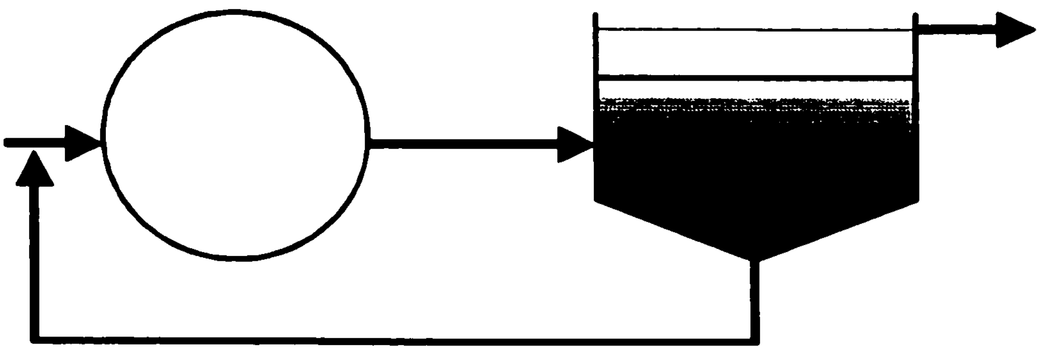

Figure 1.1: Typical activated sludge configuration of biological reactor followed by settling tank with underflow recycle.

Identifying sludge settleability is important for settler design, modelling of settler performance, and as a basis for making operating decisions. Sludge settling tests currently are conducted as batch tests, and fall into two categories:

- Zone settling velocity (ZSV) tests where the movement of the sludge-water interface is tracked. Multiple tests usually are applied over a range of initial concentrations (X_0) to provide data for establishing a two-parameter relationship (model) with ZSV as a function of X.
- Sludge volume index (SVI) tests (or variations on SVI) where the volume occupied by a known mass of solids is measured after a fixed period of settling (usually 30 minutes).

$$SVI = \frac{\left(SV_{30} / SV_0 \right)}{X_0} \cdot 1000 \qquad mL/g \qquad (1.1a)$$

For a settling vessel of uniform cross-sectional area A, if the test starts with the vessel filled to a height H_0 and the interface drops to a height H_{30} after 30 minutes, then Eq. 1.1a can be written as:

$$SVI = \frac{\left(H_{30} \cdot A / H_0 \cdot A \right)}{X_0} \cdot 1000 \qquad mL/g$$

$$= \frac{\left(H_{30} / H_0 \right)}{X_0} \cdot 1000 \qquad mL/g \qquad (1.1b)$$

SVI-type tests are simpler to perform than ZSV tests. In fact, in current practice, instead of measuring ZSV model parameters, these often are estimated using correlations based on SVI-type measurements.

Variations on the original SVI test such as the DSVI have evolved to address perceived deficiencies in the "standard" SVI test. Current consensus is that the greatest problem is that SVI changes with concentration. Figure 1.2 shows an example of the relationship between SVI and X_0 (after Dick and Vesilind, 1969).

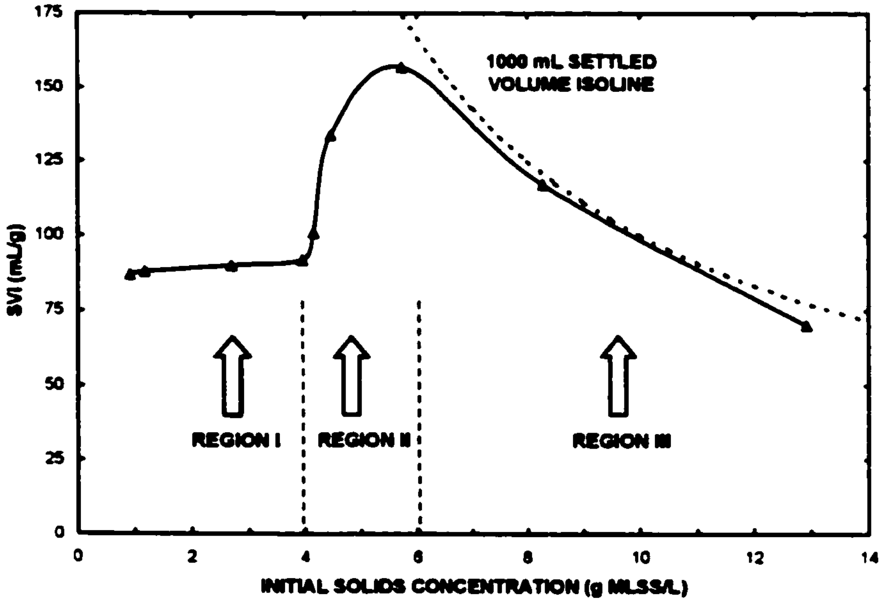

Figure 1.2: Typical SVI-solids concentration relationship (after Dick and Vesilind, 1969).

From Figure 1.2 it is evident that SVI apparently is "consistent" for lower concentrations (Region I, i.e. the DSVI range), increases rapidly to a maximum (Region II), and decreases for further increase in concentration (Region III). The last part (Region III) is simple to interpret, and is merely a consequence of how SVI is calculated. At high concentrations, if there is zero sludge settlement in the 30 minute time, the calculated SVI must decrease for increasing concentration.

The rapid increase in SVI with increasing concentration (from Region I to II) has not been explained. Rather, this concentration dependency of SVI merely has been used as the basis for criticizing SVI. [As an aside, it is evident from Figure 1.2 that the SVI for the same sludge can vary extensively over a small concentration range. That is, SVI is not a "constant", contrary to the understanding of many practitioners. The change in SVI for a given sludge, depending on concentration, calls for caution in the application of correlations for estimating ZSV parameters based on SVI. Obviously different SVI values will lead to different ZSV parameter estimates.]

1.2 OBJECTIVES

The primary objective of this study was to investigate SVI-type sludge settleability measures in an effort to provide a means for interpreting and understanding "artifacts" of these measures cited and criticized by other researchers. Specific research goals included:

- Identification of a rational basis for explaining:
    - the sensitivity of SVI-type measures to test parameters such as solids concentration and column height.
    - the relationship between the SVI and the DSVI.
- Evaluation of the approach of correlating flux theory parameters with SVI-type measures.

The approach used was to develop a simple model to approximate the behaviour in a batch settling test. The model is based on the well-established Vesilind equation relating suspended solids concentration to settling velocity and mass balances performed on a batch settling test (other equations exist and could also be used). The model was then used as a tool to illustrate some of the problems that have been identified with the SVI and as a basis for explaining these observations.

A secondary objective of the study was to evaluate the approaches to one-dimensional settler modelling. Research goals included:

- Evaluation of constraints incorporated in one-dimensional settling tank models. Is it possible to achieve a stable model without these constraints?
- Assessment of the importance of practical constraints such as maximum sludge compactability in the underflow recycle and their impacts on modelling.

The approach used was to examine two cases: a steady-state continuous flow settling tank, and an unsteady state case batch settling test. The mass balance equations for these cases were examined, and numerical solution and/or instability problems were highlighted and discussed.

This thesis is structured in the following manner:

- Background is provided in Chapter 2. Included in this section is background on settling tests used to quantify the effect of suspended solids concentration on sludge settling velocity. Chapter 2 also provides background on the development of secondary settling tank modelling. The main body of this thesis is presented as a series of four papers (Chapters 3 to 6).
- Chapter 3 introduces the commonly used sludge settleability measures, and the modelling approach used to evaluate their behaviour.
- Chapter 4 details the correlations between sludge settleability measures and the Vesilind settling velocity equation parameters V_0 and K proposed by researchers. Also included in this chapter is an evaluation of the approach of using these correlations in clarifier design and operation.
- Chapter 5 elaborates on issues raised in Chapter 3, particularly the effects of column height and the behaviour of the DSVI.
- Chapter 6 examines the one-dimensional layered model approach for both the steady state, continuous flow case and the unsteady state, batch settling case.
- Chapter 7 contains conclusions, summarizes this study's contribution to knowledge, and outlines areas which require further research.

CHAPTER TWO

BACKGROUND ON SLUDGE SETTLEABILITY

2.1 INTRODUCTION

A secondary settler can be in one of three loading states:

1. Underloaded;
2. Critically loaded;
3. Overloaded.

In an underloaded situation, solids fed to the settler are transferred directly to the bottom of the tank from where they are recycled to the biological process. In a critically loaded situation, a region of hindered settling known as the sludge blanket forms at some point in the settler depth, depending on loading conditions and settler characteristics. A critically loaded settler is shown in Figure 2.1.

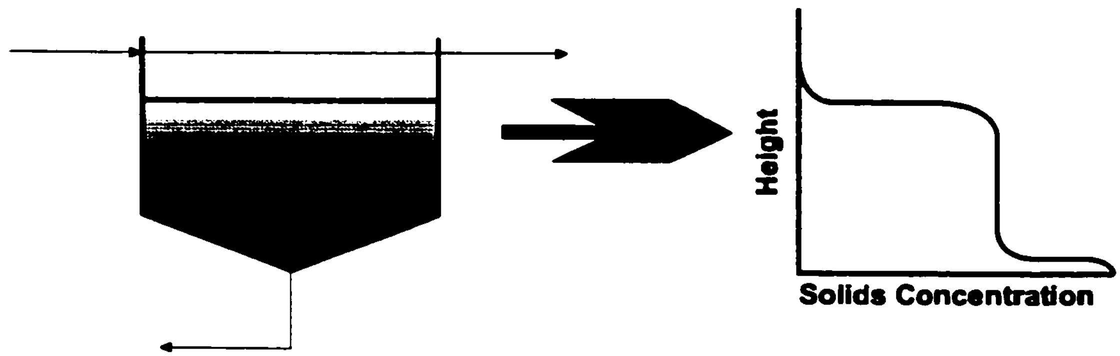

Figure 2.1: Critically loaded settler and corresponding concentration profile.

If the loading rate is increased beyond the critical value, then the third state (overloaded) exists and the sludge blanket will begin to rise towards the top of the tank. The rate at which the sludge blanket rises depends upon two factors:

1. The amount by which the overload exceeds the critical loading rate, and/or;
2. Whether the underflow recycle rate is increased.

Increasing the recycle rate may stabilize or slow down the rise rate of the sludge blanket, but for given loading conditions there will be a limiting maximum recycle rate. If the recycle rate is increased beyond this maximum value, solids will be pumped out of the bottom of the settler before they can thicken adequately and thickening failure will occur.

Because of the diurnal loading pattern on most wastewater treatment plants, it is possible for a settler to exhibit all three loading conditions during one daily cycle. The design variables of surface area, depth, underflow recycle, mass loading rate, and sludge settleability all interact to determine settler behaviour.

2.2 SETTLING TESTS

A crucial aspect of settler design and operational control strategies is the quantification of sludge settleability. A variety of sludge settleability measures exist and there is considerable confusion as to the best parameter and experimental technique to use. Essentially all settling tests subject a given mixed liquor sample to similar conditions. That is, the sample is placed in a vessel (usually a cylinder), mixed well, and then allowed to settle quiescently. The behaviour with time in a typical column settling test is illustrated in Figure 2.2.

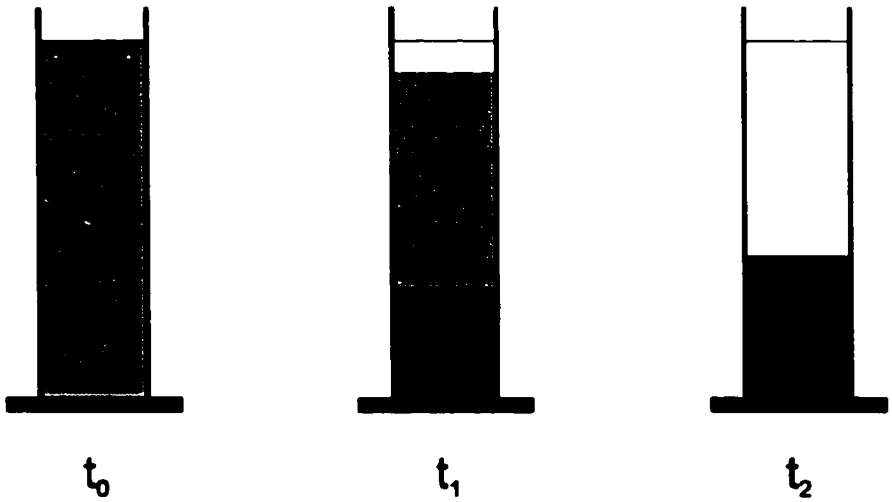

Figure 2.2: Behaviour observed in a column settling test.

At the start there may be a short period where little settlement takes place; during this phase the mixed suspended solids reflocculate and a sludge-water interface forms. The next phase is a zone (or hindered) settling portion in which the sludge-water interface settles at a constant velocity. This zone settling phase is followed by a transition stage between zone settling and compression settling. Finally, there is minimal further settling because the solids have been compacted to the highest degree possible under gravity settling conditions. Factors which may vary between testing set-ups are: (1) column height; (2) initial MLSS concentration; and (3) the inclusion or absence of slow stirring.

If a number (i.e. eight to ten) of these settling tests are performed over a range of suspended solids concentrations (e.g. 1 to 12 g/L), it may be possible to quantify the effect of solids concentration (X) on sludge zone settling velocity (V_S). A number of empirical models have been proposed; of these, perhaps the semi-logarithmic Vesilind (1968b) equation most commonly is used:

$$V_S = V_0 \; e^{-KX} \qquad (\mathrm{m/h}) \tag{2.1}$$

where V_0 and K are empirical parameters.

Flux theory often is used in the design and operation of secondary settling tanks. Application of flux theory involves setting up a flux curve, where the solids flux [product of solids concentration and zone settling velocity (V_S)] is plotted versus the solids concentration. A relationship for sludge settling velocity such as Eq. 1 is used in this analysis.

Conducting these column settling tests requires extensive experimental effort. Therefore, alternate measures of sludge settleability such as Sludge Volume Index (SVI) are more popular in practice. Other more readily measured sludge settleability parameters include Stirred Specific Volume Index (SSVI), Stirred Specific Volume Index @ 3.5 g/L ($SSVI_{3.5}$), and the Diluted Sludge Volume Index (DSVI). All of these measures historically have proven useful in monitoring plant performance on a day to day basis and evaluating trends in sludge settleability at a particular plant.

In recent literature there has been considerable debate over which settleability measure is best. For example, Lee *et al.* (1983) were particularly harsh in their criticism of SVI:

> "...it is appropriate now that the standard SVI, after over 45 years of use, be supplanted by an index more directly applicable to activated sludge process design and operation. Universal adoption of the diluted SVI as this index would represent a significant and timely advancement in the field of water pollution control."

This statement was amended by Ekama *et al.* (1997) to also include SSVI as an equally valid alternative to the SVI. Arguments against the SVI largely are based on the fact that SVI changes with concentration. As shown in Figure 1.2, SVI *does* change significantly with concentration. However, nobody has clearly and explicitly explained *why* it changes. Addressing this issue is fundamental to this thesis. At the start of this research project, the approach was that if the concentration dependence of the SVI could be explained, then perhaps it would be possible to provide a basis for suggesting the best parameter. At the outset, this seemed like a major endeavour. However, it did not turn out to be as large a problem as anticipated.

The SVI-solids concentration relationship aspect is developed in the papers forming the main body of this thesis. The basis of the explanation is presented in the following section. It is recognised that this essentially repeats material presented later. However, the fact that we ***should*** expect SVI to vary with concentration, and that SVI also may depend on settling column height is fundamental to the thesis.

2.3 SVI DEPENDANCE ON SOLIDS CONCENTRATION

In a typical settling test the sample is placed in a vessel (usually a cylinder), mixed well, and then allowed to settle quiescently. The behaviour with time in a typical column settling test is illustrated in Figure 2.3. At the start there may be a short period where little settlement takes place; during this phase the mixed solids reflocculate and a sludge-water interface forms. The next phase is a linear zone (or hindered) settling portion in which the sludge-water interface settles at a constant velocity. This zone settling phase is followed by a curvilinear transition stage between zone settling and compression settling. Finally, there is a level portion where minimal further settling takes place because the sludge has been compacted to the highest degree possible under gravity settling conditions.

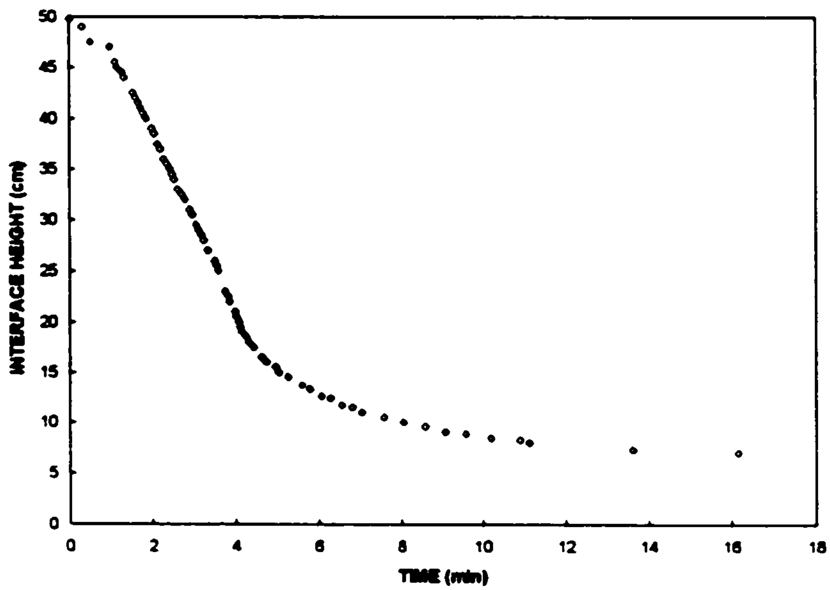

Figure 2.3: Typical column settling test solids/water interface *versus* time plot.

The SVI test starts with a column filled to a height H_0 with a well-mixed sludge sample of concentration X_0. Equation 2.1 dictates that the solids-water interface that forms under these conditions moves down the column at a constant rate, V_S. Therefore, the interface height at time *t* is given by:

$$H(t) = H_0 - V_0\, e^{-KX_0} \cdot t \qquad (2.2)$$

Figure 2.4 is an example of using Eq. 2.2 to generate an idealized representation of Figure 2.3. Also shown are the points used in SVI calculation.

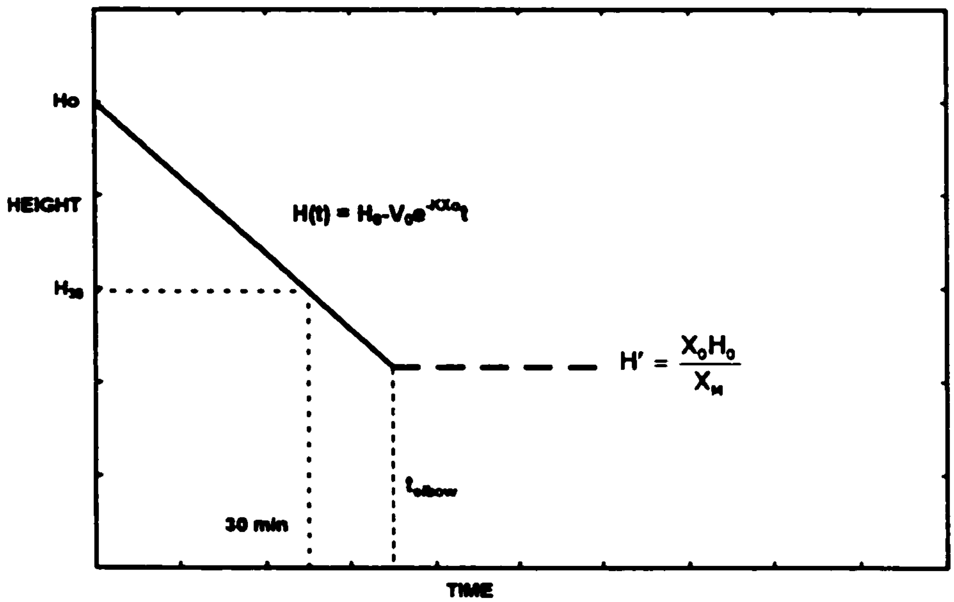

Figure 2.4: Points used in SVI calculation.

If Eq. 2.2 is substituted into Eq. 1.1, it is evident that SVI is given by (with t = 30 minutes) [Note: for the cases where t_{elbow} > 30 minutes]:

$$SVI = \frac{H_0 - \{V_0 e^{-KX_0} \cdot t\}}{X_0 H_0} \cdot 1000 \qquad (2.3)$$

This equation for SVI only is valid for the linear zone settling region, that is, if the "elbow" in Figure 2.4 occurs after the 30 minute mark. If the linear zone settling phase is finished before the 30 minute mark, the height of the 30-minute solids-liquid interface used in the calculation of SVI essentially is determined by the compactability of the sludge. If X_M represents the concentration of the compacted sludge, the height of the sludge in the column after settling is complete, H', is given by a simple mass balance:

$$X_M H' = X_0 H_0$$

$$H' = \frac{X_0 H_0}{X_M} \qquad (2.4)$$

Substituting in Eq. 1.1 yields [Note: for the cases where $t_{elbow} \leq 30$ minutes]:

$$SVI = \frac{1000}{X_M} \quad (mL/g) \qquad (2.5)$$

Equation 2.5 shows that, for any test where settling is complete before the 30 minute cut-off, SVI is only a function of the sludge compactability, X_M. That is, the SVI is "constant", irrespective of initial sludge concentration.

Equations 2.3 and 2.5 can be combined to generate a predicted SVI-solids concentration profile; an example is shown in Figure 2.5.

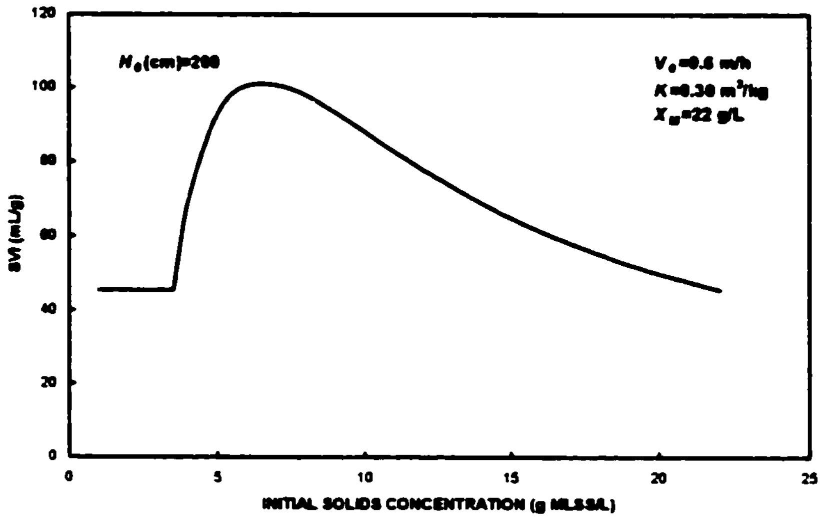

Figure 2.5: Model-generated SVI-concentration curve.

This analysis demonstrates that SVI is *expected* to change with solids concentration. In fact, the "model" curve in Figure 2.5 is very similar to the experimental one shown earlier in Figure 1.2. Later in this thesis, it also will be demonstrated that the measured SVI also is a function of the settling column height (see Eq. 2.3).

2.4 CORRELATIONS

An approach which appears to merge the benefits of flux theory analysis with the simplicity of SVI-type measures is to correlate the SVI-type measure with the ZSV=f(X) function parameters (e.g. V_0 and K in Eq. 2.1). In design, an SVI (or DSVI or $SSVI_{3.5}$) value is assumed, a correlation is used to estimate V_0 and K, and these values are applied in flux theory analysis to determine a minimum settler area to avoid thickening failure. For operations, a correlation is applied using the measured SVI, and the estimated V_0 and K values are used to assess the operating condition (principally settler underflow recycle rate) in an operating chart based on flux theory. Alternately, V_0 and K generated via correlations are used in a secondary settler model. The validity of this approach will be assessed in this thesis.

2.5 SETTLER MODELLING

Secondary settler design and analysis traditionally has relied on empirical methods employing peaking factors to take into account the impacts of dynamic loading patterns. The analytical flux theory using Eq. 2.1 as a basis can provide insight into the steady state behaviour of the settler, but is limited by its inability to predict dynamic behaviour. For example, the flux theory will tell a designer if a settler with a given surface area is overloaded for a specified loading rate, but it will not tell the designer how the depth of the settler affects its ability to handle the overload. Because of these shortcomings, it is desirable to develop a method of design and analysis that accurately represents the dynamic behaviour of secondary settlers. One method that has shown promise in this area is one-dimensional settler modelling.

The first approach to dynamic modelling of secondary settling tanks was the one-dimensional approach. Tracy and Keinath (1973) produced one of the first dynamic one-dimensional models based on a mass balance and finite difference solution methods. However, this model had problems predicting the formation of sludge blankets under certain loading conditions. This early work has formed the basis for work performed by Stenstrom (1975), Vitasovic (1985), and Takács *et al.* (1991).

More recently, other approaches to secondary settling tank modelling have been taken. Statistical modelling approaches such as Chapman (1984) concentrate on predicting effluent solids concentrations. Krebs (1991) and Zhou and McCorquodale (1992b) have formulated two-dimensional hydrodynamic models. Although these two-dimensional models have shown promise, they rely on complex finite difference schemes that are computationally intense, which limits their applicability in commonly used process simulators. Because of this, there is still interest in formulating a good one-dimensional model.

The traditional approach to one-dimensional modelling has been to divide the depth of the settling tank into a number of layers of equal thickness. Next, a ZSV model such as Eq. 2.1 is applied so that mass balances can be performed around each layer. Solving the mass balance equations essentially is obtaining a finite difference solution to the partial differential equation known as the continuity equation:

$$\frac{\partial X}{\partial t} = \frac{\partial G}{\partial z} \tag{2.6}$$

where X is solids concentration, t is time, G is solids flux in the vertical direction, and z is distance in the vertical direction.

The objective of solving the mass balance equations is to obtain an approximation of the solids concentration profile over the depth of the settling tank. If this can be done with reasonable accuracy, then effluent suspended solids concentrations and sludge blanket movement may be estimated. However, from the beginning this approach has been plagued by mathematical solution problems. A popular method of dealing with these solution problems has been the introduction of empirical constraints and parameters, which may seem to help in obtaining a solution but are not always based on sound theory.

Recently, researchers have begun to question the use of Eq. 2.1 in one-dimensional settler modelling. Equation 2.1 relates solids concentration to settling velocity, but only for the concentration range where hindered settling occurs. At low concentrations (< 1,000 mg/L, approximately), Eq. 2.1 does not describe the settling velocity accurately when solids are flocculated poorly. Eq. 2.1 tends to predict unrealistically high settling velocities at low concentrations. Recognising this, Takács *et al.* (1991) proposed a double-exponential settling velocity model that divided suspended solids into four concentration regions with different settling characteristics in each region. This has lead to improvements in model predictions of behaviour in the zone above the sludge blanket. Eq. 2.1 also does not apply at high concentrations where compressive thickening forces come into effect. Vaccari (1984) recognised this and applied a settling velocity model which attempts to account for compressive thickening behaviour.

The main criticism that has been directed at existing one-dimensional models is of the constraints and assumptions that have been incorporated into them. Two examples of constraints employed in one-dimensional models are:

- The mass flux into a differential volume cannot exceed the mass flux the volume is capable of passing, nor can it exceed the mass flux which the volume immediately below it is capable of passing
- An empirical threshold concentration X_t is arbitrarily defined to describe behaviour in the upper section of the settler. When the solids concentration is greater than X_t, it is assumed that the settling flux in that layer will affect the rate of settling within adjacent layers. It is presumed that the threshold concentration corresponds to the onset of hindered settling and defines the location of the sludge blanket.

Are these assumptions realistic? Or are they simply a matter of convenience used in order to obtain a stable numerical solution? Researchers such as Jeppsson (1996) and Diehl (1995a) have criticized these *ad hoc* assumptions. For example, Jeppsson (1996) notes that the first assumption above should not be used. Numerical algorithms should instead deal with the possible mass flux into a specific layer. Jeppsson (1996) employed a novel mathematical approach formulated by Diehl (1995a) in a robust model of the settling tank that does not rely on any of these assumptions. However, this model is highly theoretical in nature, and does not take into account such factors as maximum sludge compactability in the underflow recycle. Also, Jeppsson concedes that although the new model is superior in predicting theoretical results, it may not necessarily be better at predicting full-scale settling tank results.

CHAPTER THREE

SVI-TYPE SETTLEABILITY MEASURES: IMPACT OF BIOSOLIDS CHARACTERISTICS AND TEST PARAMETERS

This chapter contains the complete text of a paper published in *Water Environment Research*. The full reference is:

Bye C. M. and Dold P. L. (1998) Sludge volume index settleability measures: effects of solids characteristics and test parameters, *Water Environment Research*, **70**, 87-93.

SVI-TYPE SETTLEABILITY MEASURES: IMPACT OF BIOSOLIDS CHARACTERISTICS AND TEST PARAMETERS

Christopher M. Bye and Peter L. Dold

ABSTRACT

SVI-type activated sludge settleability measures are used in the design and control of secondary settling tanks. Considerable confusion exists as to the best parameter and experimental technique to use. The common settleability measures (SVI, DSVI, SSVI, and SSVI @ 3.5 g/L) are outlined. This is used as the basis for commenting on the validity of these measures and their relation to zone settling velocity (ZSV) measurements. A simple mechanistic model is used to evaluate the effects of biosolids characteristics and test parameters on SVI-type indices. Biosolids settleability and compactability, settling column height, and biosolids concentration in the test have an interactive effect on the measured SVI. The model explains many of the artifacts associated with SVI and questions the validity of correlations for zone settling parameters based on SVI-type measures.

Key words: activated sludge, settleability, flux theory, zone settling velocity, SVI, DSVI, SSVI.

INTRODUCTION

Secondary settling tanks play an important role in the performance of suspended growth activated sludge processes. Flux theory often is used in the design and operation of these tanks. Application of flux theory involves setting up a flux curve, where the solids flux [product of solids concentration and zone settling velocity (ZSV)] is plotted *versus* the solids concentration as shown in Figure 3.1. A number of hindered settling tests must be conducted to determine the ZSV over a range of suspended solids concentrations. Once the experimental data have been gathered, two approaches can be used to set up the flux diagram, as shown in Figure 3.1:

- Directly from the experimental data: Each column settling test provides one ZSV value for one solids concentration (*X*). The product of each data pair yields one data point in the flux *versus* solids concentration diagram. A flux curve is then drawn through the data points.

- Via a function relating ZSV and solids concentration: A number of empirical models have been proposed for quantifying the influence of solids concentration (*X*) on ZSV (V_S). Of these, perhaps the semi-logarithmic Vesilind equation is most commonly used:

$$V_S = V_0 e^{-KX} \qquad (m/h) \qquad (1)$$

where V_0 and K are empirical parameters. To set up the flux curve, the equation first is fit to the experimental ZSV *versus* X data by regression to yield the empirical parameters. The flux curve then can be generated as a continuous function using Eq. 1.

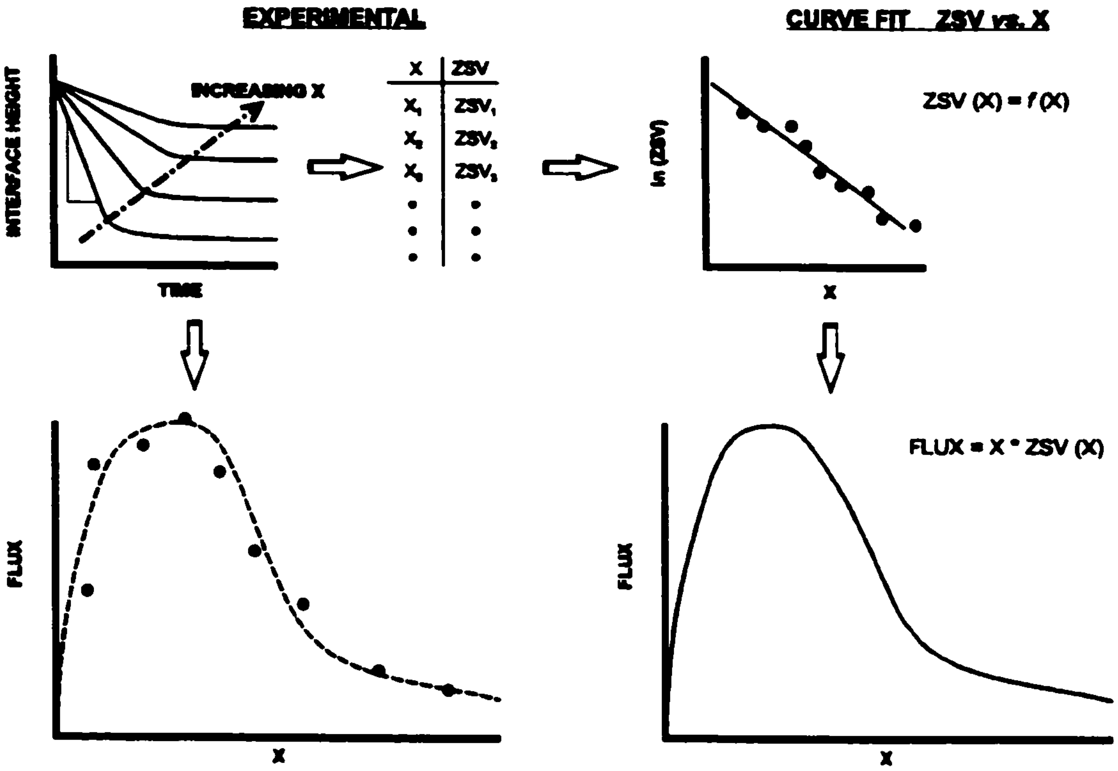

Figure 3.1: Setting up the flux curve.

Setting up the flux curve using either approach requires extensive experimental effort to measure ZSV's over a range of solids concentrations (at least eight column settling tests). Because of the effort involved, this method is not used widely, and alternate measures of biosolids settleability such as Sludge Volume Index (SVI) are more popular in practice. Other more-readily measured sludge settleability parameters include Stirred Specific Volume Index (SSVI), Stirred Specific Volume Index @ 3.5 g/L ($SSVI_{3.5}$), and the Diluted Sludge Volume Index (DSVI).

An approach which merges the benefits of flux theory analysis with the simplicity of SVI-type measures is to correlate the SVI-type measure with the ZSV *versus* X function parameters (e.g. V_0 and K in Eq. 1). Koopman and Cadee (1983) attempted to relate both V_0 and K as functions of the DSVI. Pitman (1984) developed a relationship between the quotient V_0/K and $SSVI_{3.5}$, as well as a relationship between V_0/K and SVI. However, the latter was found to exhibit a poor fit to available data. Based on Pitman's data, Ekama and Marais (1986) proposed a relationship between K and the quotient V_0/K

that could be used to separate the two parameters. Daigger and Roper (1985) proposed a relationship between the parameter K and SVI, treating V_0 as a constant. Wahlberg and Keinath (1988) developed correlations to estimate V_0 and K as separate functions of "stirred" SVI. Daigger (1995) updated his earlier relationships using an expanded database. Ozinsky and Ekama (1995) used a rigorous statistical approach to group selected databases, and proposed a number of correlations for V_0 and K based on SVI, DSVI and SSVI. Sekine *et al.* (1989) and Härtel and Pöpel (1992) are further examples of using correlations for V_0 and K based on SVI-type measures. This approach seems to have gained quite widespread acceptance.

OBJECTIVES & APPROACH

There has been extensive debate on the subject of quantifying biosolids settleability. Issues include:

- Which of the SVI-type parameters provides the "best" measure of biosolids settleability?
- There is considerable confusion regarding methodology in the various settleability measures, especially concerning the inclusion or absence of stirring, and the size of the apparatus used in the test.
- The SVI of a given mixed liquor sample depends on the solids concentration used in the test.
- Regarding correlations for V_0 and K, mathematically it would appear somewhat dubious that two parameters in a model such as Eq. 1 which quantifies how solids concentration (X) influences ZSV can be estimated based on a single SVI value from a test conducted at a single X_0 value.

This paper discusses the various biosolids settleability measures and addresses the problems identified above. The approach is based on a simple mechanistic model for predicting behaviour in a column settling test. The model can be used as a basis for evaluating the impact of different variables (cylinder height, biosolids compactability, zone settling characteristics) on the different tests. This modeling approach provides an elegant method for assessing the relevance of the different techniques as valid measures of biosolids settleability and whether it is valid to correlate ZSV model parameters to SVI-type measures.

BIOSOLIDS SETTLEABILITY MEASURES

Essentially all settling tests subject a given mixed liquor sample to similar conditions. That is, the sample is placed in a vessel (usually a cylinder), mixed well, and then allowed to settle quiescently. The behaviour with time in a typical column settling test is illustrated in Figure 3.2. At the start there may be a short period where little settlement takes place; during this phase the mixed biosolids reflocculate and a biosolids-water interface forms. The next phase is a linear zone (or hindered) settling portion in which the biosolids-water interface settles at a constant velocity. This zone settling phase is followed by a curvilinear transition stage between zone settling and compression settling. Finally, there is a level portion where minimal further settling takes place because the biosolids have been compacted to the highest degree possible under gravity settling conditions. Factors which may vary between testing set-ups are: (1) column height; (2) initial MLSS concentration; and (3) the inclusion or absence of slow stirring. Dick and Vesilind (1969) proposed that stirring in a column settling test aids in the agglomeration of the biosolids and minimizes the effects of bridging within the biosolids mass. White (1976) felt that stirring also helped to minimize wall effects which tend to result in poor settling behaviour.

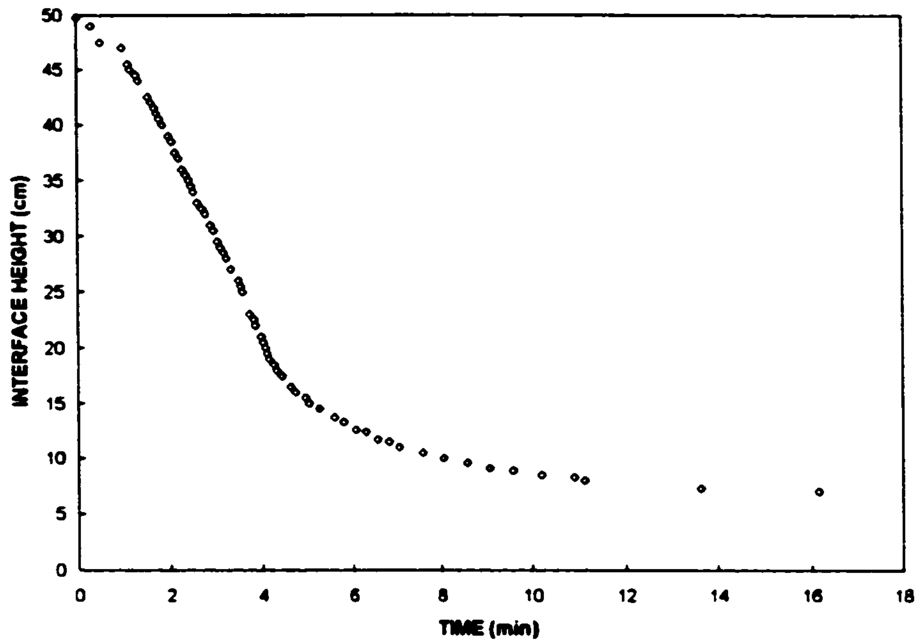

Figure 3.2: Typical settling profile.

Sludge Volume Index (SVI)

The SVI is the most common parameter used to quantify the settling characteristics of suspended growth activated sludge biosolids. This is due primarily to the simplicity with which the test is performed. According to Standard Methods (1971), the SVI has "no basis in solid-liquid separation theory but has been found empirically to be of considerable value."

The main criticism of the SVI is that there is no consistent relationship between suspended solids concentration and the SVI, as first noted by Dick and Vesilind (1969). For a given sample, the SVI tends to be constant with increasing concentration up to a certain value. At this point, there is a rapid increase in SVI with a further increase in concentration. The increase in SVI continues until a peak value is reached, after which the SVI begins to *decrease* with increasing solids concentration. Typical SVI - Solids Concentration curves illustrating this behaviour are shown in Figure 3.3 (Dick and Vesilind, 1969). Also shown in Figure 3.3 are dashed isolines which represent two different scenarios. The upper isoline represents the SVI when no settlement has taken place at a particular concentration. The lower isoline is for the case where the 30 minute settled volume (SV_{30}) is 250 mL in a 1000 mL test volume.

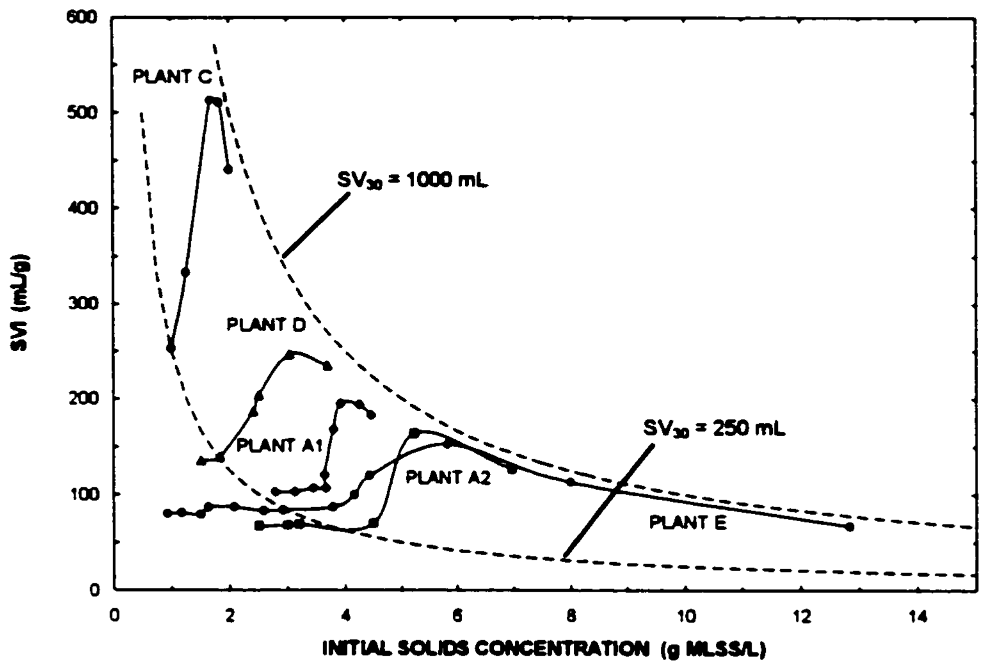

Figure 3.3: Typical SVI - solids concentration relationship (after Dick & Vesilind, 1969).

Confusion continues to exist with regard to the procedure of the SVI test. Prior to the 15[th] edition of Standard Methods (i.e. pre - 1980) the methodology for the SVI test did not specify stirring as a requirement. It was first noted by Dick and Vesilind (1969) that the inclusion of slow stirring in the test had an impact on the SVI for a given sample as shown in Figure 3.4. For the same sample, the SVI conducted with slow stirring yielded consistently lower values than those obtained by conducting the test without stirring. Also, the stirred SVI was less dependent on concentration than the unstirred test; however, the stirred SVI does not overcome the impact of solids concentration completely as illustrated in Figure 3.4. The procedure for conducting the SVI test outlined in Standard Methods was modified in 1980 to include slow stirring between 1 and 2 rpm. Nevertheless, in practice the SVI often is performed as an unstirred test.

Diluted Sludge Volume Index (DSVI)

The DSVI apparently was first used in Germany in 1972, reportedly to alleviate the effects of bridging (White, 1976). Ekama and Marais (1984) noted that the SVI does not vary with solids concentration if the 30 minute settled volume is less than approximately 250 mL. This is evident in Figure 3.3. They proposed that the test sample should be diluted serially until the observed 30 minute settled volume is less than 200 mL. This SVI is then reported as the DSVI. In effect, the DSVI simply "moves backwards" along the SVI - Solids Concentration curves shown in Figure 3.3 through successive sample dilutions until the initial constant portion is attained. The 200 mL 30 minute settled volume is chosen arbitrarily as a value that will ensure that this "constant" SVI condition is reached for most samples.

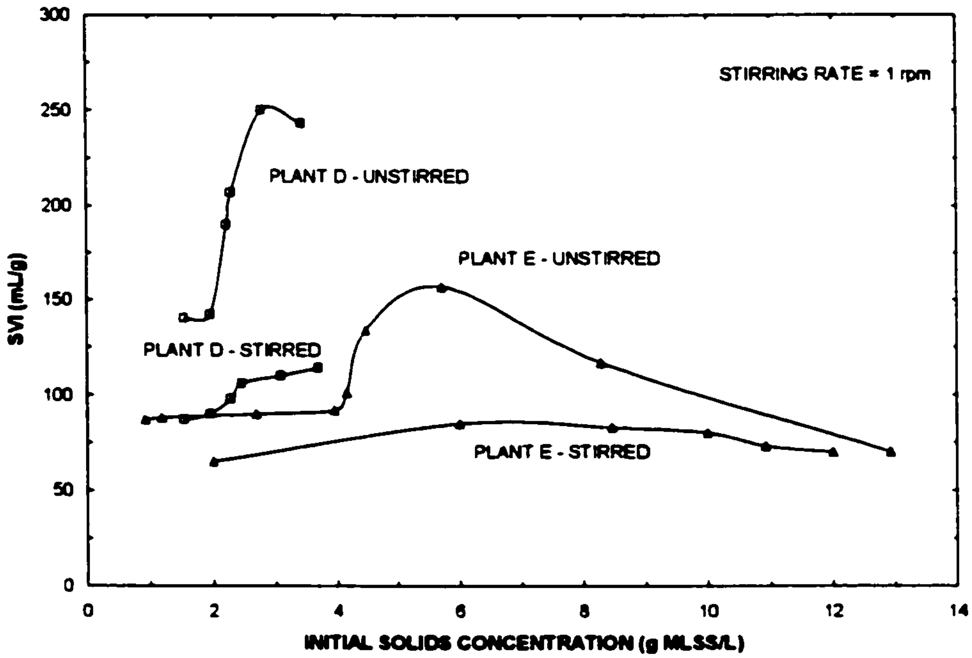

Figure 3.4: Effect of stirring on SVI (after Dick & Vesilind, 1969).

Stirred Specific Volume Index (SSVI and $SSVI_{3.5}$)

White (1976) confirmed many of the problems with the original (unstirred) SVI first noted by Dick and Vesilind (1969). As a result, he proposed a new settleability measure, the SSVI. The procedure for this measure is identical to the SVI procedure which has been outlined in Standard Methods since 1980 (i.e. with stirring). However, the equipment is somewhat different. White suggests the settling column used should have a 100 mm diameter and depth of 500 mm which gives a total volume of about 4 L, as opposed to Standard Methods' suggestion of a 1 L settling column (depth approximately 350 mm).

White (1976) measured the SSVI at different concentrations of biosolids from 30 activated sludge systems. For each system the SSVI data were plotted against solids concentration and the SSVI at a solids concentration of 3.5 g/L was interpolated. The value of 3.5 g/L was chosen as a reference for reporting SSVI (i.e. $SSVI_{3.5}$) because:

- this is a concentration which appears commonly in activated sludge plants as mixed liquor or return sludge.
- the correlation between SSVI and the rate of hindered settling tends to be poor at concentrations below 3.5 g/L.

White (1976) also determined the zone settling parameters V_0 and K. These parameters were used to set up a solids flux curve and predict a maximum solids loading for an underflow rate of 0.6 m/h. The maximum solids loading rates were then plotted against the $SSVI_{3.5}$ for all of the data. This exercise revealed a linear correlation between the maximum solids loading rate and the $SSVI_{3.5}$.

The $SSVI_{3.5}$ has been widely adopted as the principal settleability measure in England, and is used extensively for the design and control of secondary clarifiers. There are several reasons for this popularity (Ekama and Marais, 1984):

1. For a given sludge, reproducible results for the relationship between SSVI and solids concentration are obtained for concentrations up to 10 g/L for good settling sludges and 7 g/L for poor settling sludges. [However, it should be noted that this conflicts with the observation of White (1976) that the correlation between SSVI and settling rate is poor for concentrations below 3.5 g/L].

2. The 30 minute settled volume fraction may be as high as 0.7 - 0.8 without adversely affecting the test results.

3. The relationship between the 30 minute settled volume fraction and solids concentration appears to be close to linear. There seem to be some inconsistencies with regard to this point, since it was noted by Dick and Vesilind (1969) that although stirring improves the behaviour of the SVI, the solids concentration dependence is not eliminated; that is, the plot of SV_{30} *versus* X_0 would not be linear.

SIMULATION OF SETTLING TEST BEHAVIOR

A simple model was developed to assess the impact of variables in settling tests (column height, initial MLSS concentration, biosolids compactability, etc.). The model is based on three assumptions which identify three phases in the simulated settling test:

Phase 1: At the outset of the test there may be a period of reflocculation before sedimentation begins. This is modeled by the inclusion of a short "dead" time, t_F, during which no settlement occurs. If there is no lag phase at the start then t_F will be zero.

Phase 2: During sedimentation the downward velocity of the biosolids-water interface is governed by the zone settling model (Eq. 1). Applying Eq. 1, the linear change in interface height as a function of time is given by:

$$H(t) = H_0 - V_0 e^{-KX_0}(t - t_F) \qquad (m) \qquad (2)$$

where H_0 is the initial height of the sample in the settling column, X_0 is the initial biosolids concentration, and $(t - t_F)$ is the time from the start of the sedimentation phase. The end of this linear phase of zone settling is determined by the biosolids compactability (see below).

Phase 3: It is assumed that, for a given mixed liquor, the final settled solids volume is directly proportional to the initial biosolids concentration. That is, a mixed liquor sample exhibits a certain maximum biosolids compactability, X_M (units of g/L). This assumption has been verified with data sets from a number of treatment plants; Figure 3.5 presents an example data set. The maximum biosolids compactability, X_M, is obtained by taking the inverse of the slope of the line in Figure 3.5. This assumption implies that Phase 2 continues until the biosolids interface has reached a point where the concentration of solids at the base of the column has attained the maximum compactability, X_M. From a mass balance, the final settled height in the column, *H'*, is given by:

$$H' = \frac{X_0 H_0}{X_M}(m) \tag{3}$$

A graphical representation of the simulated interface height in a settling test is shown in Figure 3.6.

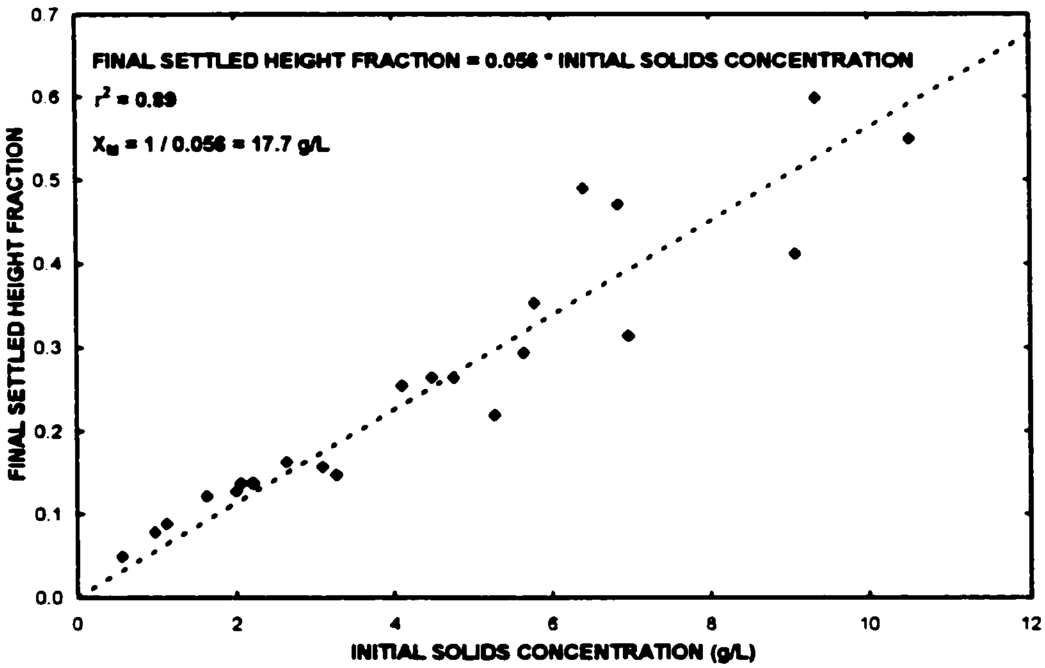

Figure 3.5: Relationship between solids concentration and final settled height.

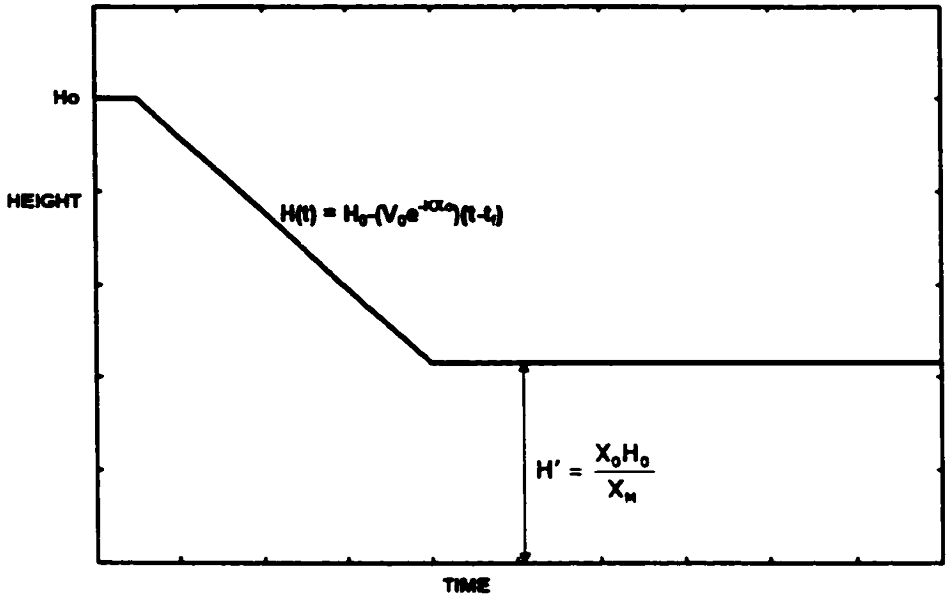

Figure 3.6: Model used to generate settling profile.

The model can be used to generate an SVI - Solids Concentration profile for a given biosolids sample by the following procedure. First, the biosolids settling parameters (V_0 and K), the biosolids compactability (X_M) and the settling column height (H_0) are specified. [If an initial lag phase is to be modeled t_F also must be specified]. The model then is applied to generate a series of solids interface height profiles for a range of solids concentrations. An example is shown for four solids concentrations in Figure 3.7. Next, the SVI for each concentration is calculated by computing the fractional settled height at 30 minutes, dividing this value by the initial solids concentration X_0, and multiplying by 1000 to normalize to a one litre cylinder. Whether the "elbows" in Figure 3.7 occur before or after 30 minutes is crucial in determining the shape of the SVI - Solids Concentration curve.

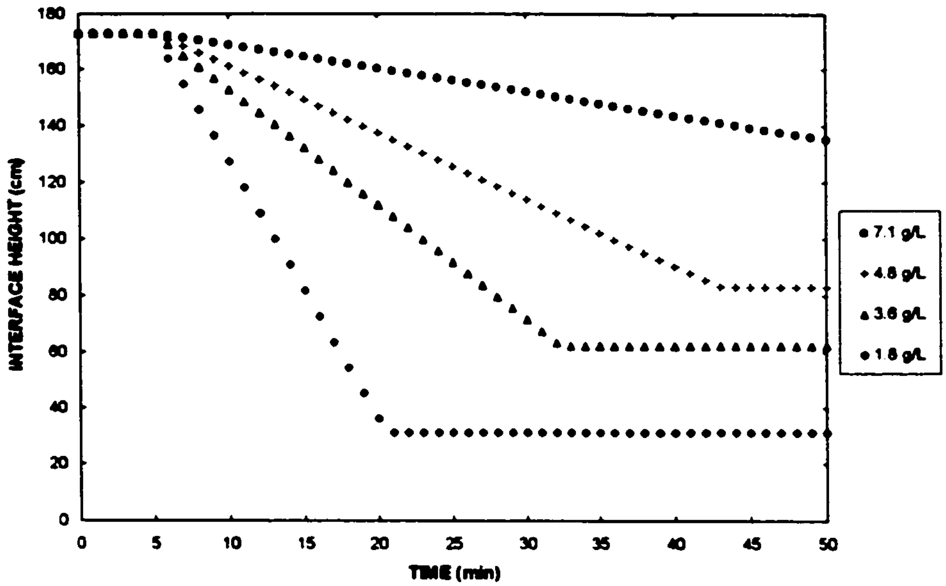

Figure 3.7: Model application to biosolids sample at different concentrations.

If the biosolids interface has not reached the compacted height H' by 30 minutes (i.e. the "elbow" occurs after 30 minutes), the interface height is governed by Eq. 2. Therefore, the SVI is a function of the initial solids concentration and the zone settling parameters:

$$SVI = \left\{ \frac{H_0 - \left[V_0 \, e^{-KX_0} (0.5 - t_F) \right]}{XH_0} \right\} \times 1\,000 \qquad (mL/g) \qquad (4)$$

Equation 4 illustrates that the SVI during Phase 1 is a non-linear function of solids concentration for a given sample and test conditions.

If the biosolids interface has settled rapidly and reached the level portion with interface height H' by 30 minutes or less (i.e. the "elbow" occurs before 30 minutes), then Eq. 4 can be simplified using the relationship between H' and H_0 from Eq. 3, and the SVI is given by:

$$SVI = \frac{1000}{X_M} \qquad (mL/g) \qquad (5)$$

Equation 5 reveals two important details about the SVI (and DSVI):

- The SVI is independent of solids concentration as long as the column settling test has reached compression settling by 30 minutes or less. This explains the initial flat portion of the SVI - concentration curves as first noted by Dick and Vesilind (1969).

- Equation 5 is a function only of the compactability of a given sample. Any SVI-type measure that is taken when compression settling has been achieved within 30 minutes or less reveals nothing about the settling characteristics of the biosolids. That is, DSVI only relates to biosolids compactability.

An example of an SVI - Solids Concentration profile generated by the model for a given biosolids sample over a range of concentrations is shown in Figure 3.8. It is evident that the model generates the same trend in SVI with increasing biosolids concentration as shown for experimental data in Figure 3.3; namely:

- At lower concentrations (X_0 < 3 g/L in this case) the SVI is constant for increasing concentration (approximately 45 mL/g).

- As test concentration increases there is a rapid increase in SVI to a maximum (approximately 100 mL/g at X_0 = 6 g/L in this case).

- For further increases in concentration the SVI decreases, following a curve which represents little or no settlement in the test.

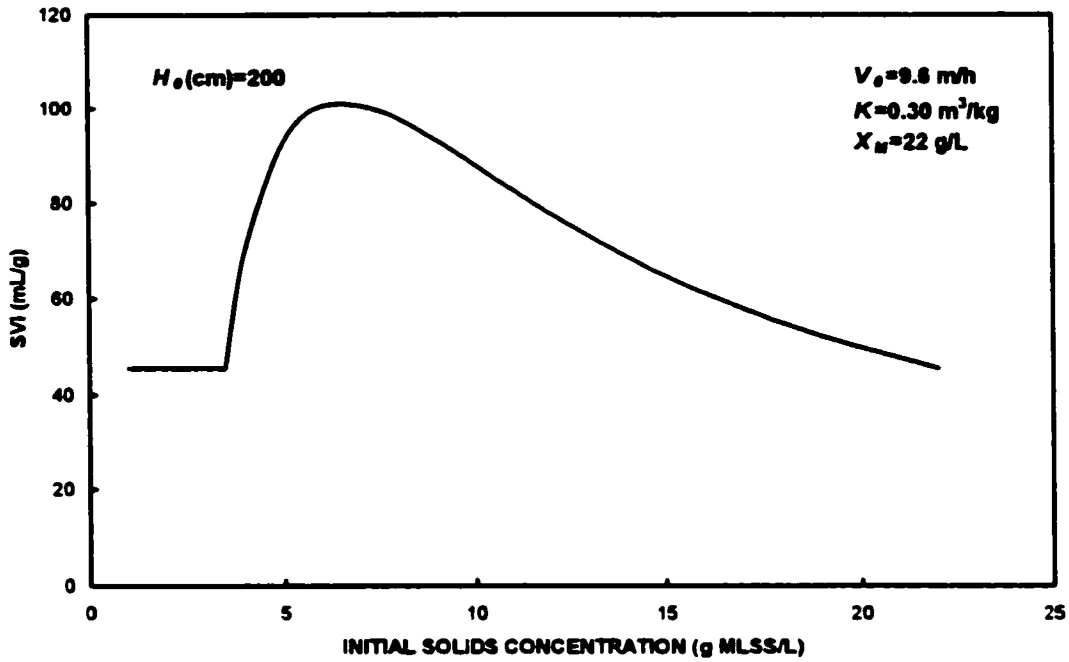

Figure 3.8: Typical model-generated SVI versus X_0 profile.

To assess the validity of the assumptions detailed previously, the model was fit to settling data sets obtained from several full-scale treatment plants. An example of this is illustrated in Figure 3.9, which illustrates the excellent fit to the data exhibited by the model. The trend predicted by the model consists of three distinct sections. Initially the SVI is constant with increasing concentration. This section is followed by a rapid increase in SVI with further increase in concentration up to a peak value. Finally, the SVI begins to decrease with further increase in concentration.

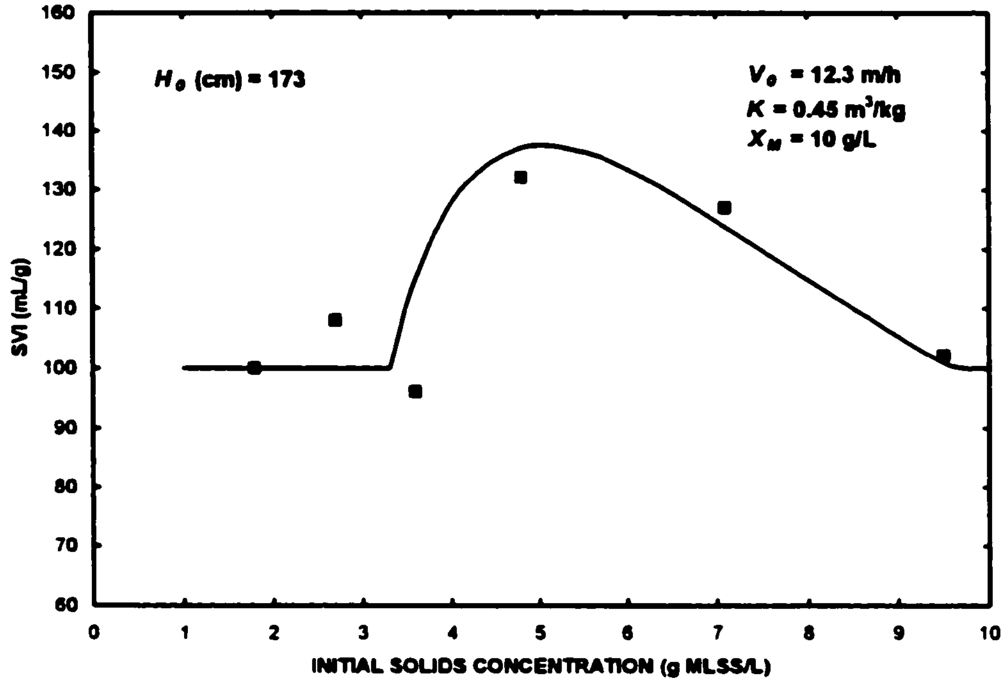

Figure 3.9: Validation of model with full-scale treatment plant settling data.

MODEL APPLICATION

The model can be used to investigate how column height (H_O), zone settling characteristics (V_O and K) and biosolids compactability (X_M) impact the SVI - Solids Concentration relationship.

Column Height

SVI *versus* X_O curves for tests in columns with heights of 50, 100, 150 and 200 cm were generated for a biosolids sample with fixed settling characteristics and compactability; the modeling results appear in Figure 3.10. Each case shows the SVI trend with increasing solids concentration evident in Figure 3.3. It is also evident that:

- The range of possible SVI values from the minimum attainable SVI (i.e. the DSVI) to the peak SVI increases with increasing column height. For the 50 cm column SVI essentially is independent of solids concentration because the biosolids interface height in the short column has reached H' at or before 30 minutes for all but the highest concentrations. For the 200 cm column the SVI values range from 83 to 160 mL/g. Also, the biosolids concentration at which the maximum attainable SVI occurs decreases as H_0 increases. The range of possible SVI values from the minimum attainable SVI to the peak SVI (SVI_{MAX}) is given by the difference of Eqs. 4 and 5:

$$SVI_{MAX} - DSVI = \left[\frac{H_0 - \{V_0 e^{-kX_0} \cdot (0.5 - t_F)\}}{X_0 H_0} - \frac{1}{X_M}\right] \cdot 1000 \text{ (mL/g)} \qquad (6)$$

Two points are illustrated by Eq.6:

1. The reason for the increasing range of SVI values with increased column height is evident from examination of Eq. 6. For a biosolids sample with fixed settling characteristics and compactability, the numerator of the first term in Eq. 6 increases at a greater rate than the denominator with increasing H_0. The second term depends only on the biosolids compactability and remains constant as H_0 varies. Therefore, the overall effect is for the range of possible SVI values to increase with increasing H_0.

2. The explanation for the maximum range occurring at lower biosolids concentrations as H_0 increases is also obtained from examination of Eq. 6. As H_0 is increased, the maximum attainable SVI occurs at lower X_0 values since the denominator of the first term of Eq. 6 is given by the product of these two variables. The second term again depends only on the biosolids compactability and remains constant. The overall effect is that the maximum SVI occurs at lower X_0 values as H_0 increases.

For a given test case, it is possible to estimate the maximum attainable SVI and the corresponding biosolids concentration using Eq. 6. It is a differentiable function, but its non-linearity makes it difficult to solve explicitly. A simpler approach is to use numerical methods to find the maximum attainable SVI and the corresponding biosolids concentration.

- In each case, as concentration increases, at some point there is a transition from the constant SVI (i.e. the DSVI) to an increasing SVI. The transition occurs at lower concentrations as column height increases. This is a consequence of the difference in (H_0 - H'). With a shorter column, the distance that must be covered to reach H' is decreased, making it easier for the biosolids interface to reach H' at or before the 30 minute mark. Thus as column height decreases, a greater number of biosolids concentrations are able to reach H' at or before 30 minutes, making the SVI less dependent on solids concentration.

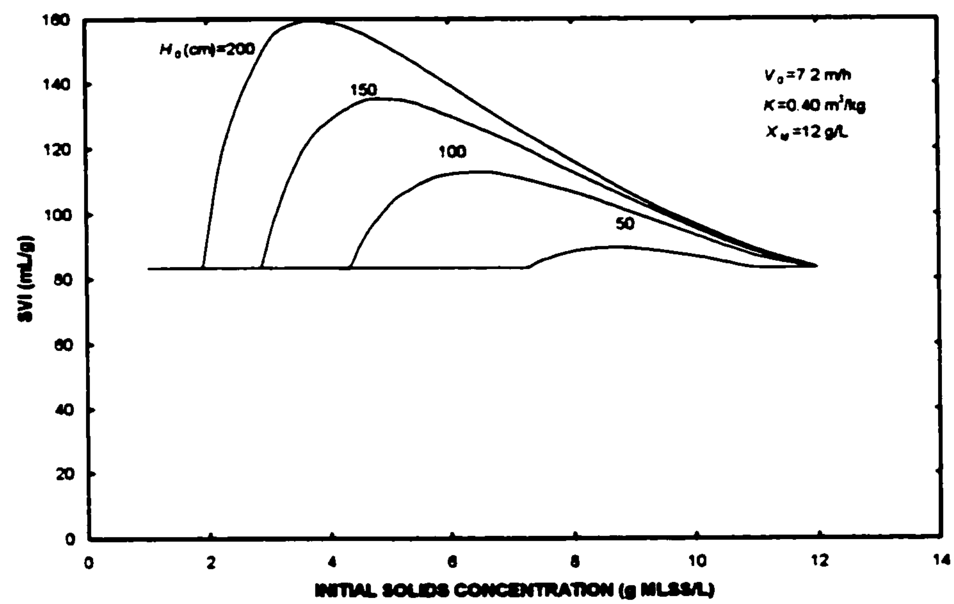

Figure 3.10: SVI - solids concentration curve for different settling column heights.

Zone Settling Characteristics

The results in Figure 3.10 were generated for a "poor" settling biosolids sample with a low V_0 of 7.2 m/h and a high K of 0.40 m^3/kg, and an intermediate compactability X_M of 12 g/L. To illustrate the effect that the zone settling characteristics have on the SVI - Solids Concentration relationship, the SVI-X_0 curves in Figure 3.10 ("poor" settling characteristics) were regenerated for the same set of parameters, but for changed V_0 and K (a higher V_0 of 9.6 m/h and a lower K of 0.30 m^3/kg). The results for this sample with "good" settling characteristics are shown in Figure 3.11. From a comparison of Figure

3.10 and Figure 3.11 it is evident that the effect of column height is less pronounced when the biosolids have "good" settling characteristics. In Figure 3.11 SVI is independent of solids concentration for both the 50 and 100 cm columns. This is because the biosolids interface height has reached H' at or before 30 minutes for all concentrations with the rapidly settling sample. Even for the 150 cm column, SVI dependence on solids concentration is minimal. For the 200 cm column, the SVI values range from 83 mL/g to 100 mL/g, which is a much smaller range than for the case of "poor" settling solids.

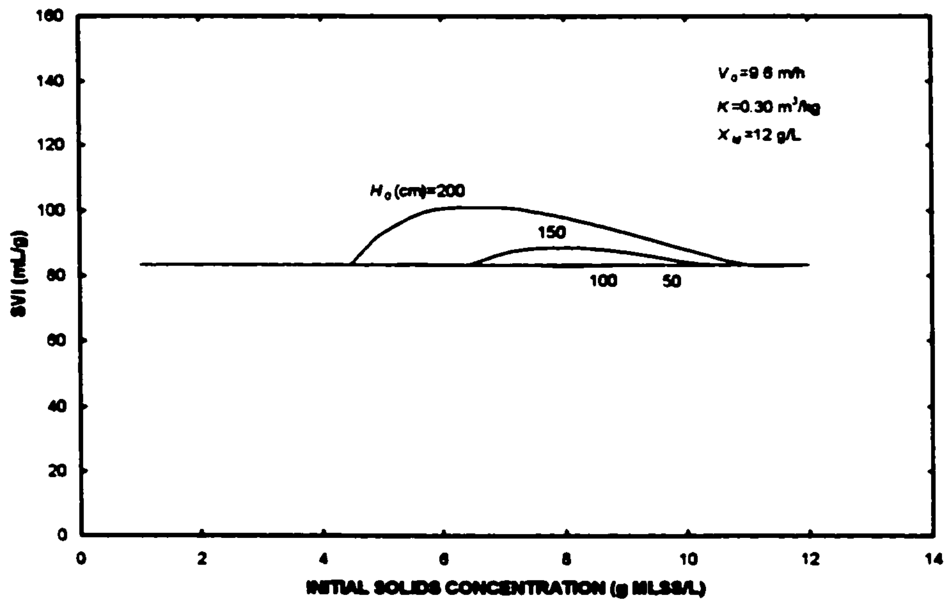

Figure 3.11: SVI - solids concentration curve for different settling column heights.

Biosolids Compactability

For both cases in Figure 3.10 and Figure 3.11 the biosolids compactability was held constant at an intermediate value of 12 g/L. In each case the DSVI of the samples was 83 mL/g (from Eq. 5). Additional simulations were performed to illustrate the effect of biosolids compactability (X_M). Figure 3.12 shows the results for the "poor" settling case in a column of height 200 cm, but for biosolids compactabilities of 8, 12, 16 and 20 g/L.

It is evident from Figure 3.12 that the effect of biosolids compactability on the SVI *versus* solids concentration relationship is quite significant. Again, for each case the SVI *versus* X_0 curve is of the form in Figure 3.3, but the possible SVI range increases with increasing compactability. The reason for this can be seen readily by examining Eq. 6. For a given test case over a range of biosolids concentrations with fixed column height H_0 and settling characteristics V_0 and K, the first term of Eq. 6 is unaffected by changes in X_M. The second term is reduced by increasing X_M. Since the second term is subtracted from the first, the effect of reducing the second term is to increase the range. In each case the maximum SVI is fixed but the minimum achievable SVI (i.e. the DSVI) decreases as compactability increases according to Eq. 5. When the biosolids have a low compactability of 8 g/L, the SVI ranges from 125 mL/g to 160 mL/g. When the biosolids compactability is increased to a high value of 20 g/L, the SVI ranges from 50 mL/g to 160 mL/g.

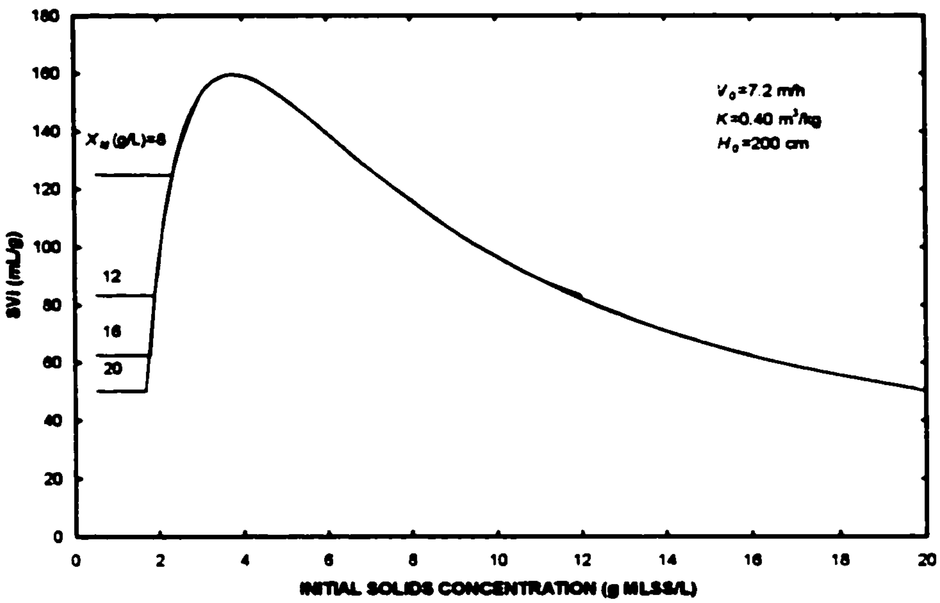

Figure 3.12: SVI-solids concentration curve for different biosolids compactabilities.

CONCLUSIONS

The model provides a simple, yet elegant, means for interpreting settling test behaviour. The model serves as a tool to demonstrate the interactive impact of test column height, biosolids concentration and compactability, and zone settling characteristics on SVI results. Many of the artifacts associated with the SVI cited by researchers over the years are explained logically using the model; for example, the relationship of DSVI to SVI.

Three important conclusions are:

- Depending on the test conditions (column height, biosolids settleability and compactability), SVI may show a marked dependence on the biosolids concentration. For example, from Figure 3.12 with a compactability of 20 g/L the SVI changes threefold from 50 to 160 mL/g if the test is performed at a biosolids concentration of 1.8 or 3.8 g/L.

- The DSVI test "forces" the SVI test conditions into the region where SVI is independent of solids concentration. Intuitively it may seem that this is a suitable measuring state. However, in this region the observed SVI bears no relation to the settleability of the test sample. Rather, the DSVI only provides a measure of biosolids compactability.

- The results presented in the paper question the validity of the correlations for zone settling parameters based on DSVI or SVI. With regard to DSVI, comparing Figure 3.10 and Figure 3.11, it is evident that two samples with very different zone settling parameters (V_0 and K) will have the same DSVI. However, a correlation based on DSVI will predict the same V_0 and K. With regard to SVI, the results have shown that a sample with given zone settling parameters (V_0 and K) can exhibit a wide range of SVI values even for small variations in concentration in the test. However, a correlation based on SVI will predict widely different pairs of V_0 and K values.

The term "bulking" has not been used up to this point in the paper. This may seem unusual in an analysis of SVI and biosolids settleability, given that SVI is widely accepted as an indicator of bulking in practice. It has been demonstrated that DSVI is directly linked (and inversely related to) the biosolids compactability parameter. Intuitively it would seem reasonable to expect that a biosolids sample with extensive filamentous bulking would be characterized by a poor compactability, and hence a high DSVI. The same link is not true necessarily for SVI, depending on the measuring regime. For example, in the case of Figure 3.12, if the test is conducted at concentrations of 4 g/L on samples with different compactabilities (and likely different extents of bulking), the SVI value is the same. This indicates that SVI *per se* is not necessarily a good measure for monitoring bulking. Rather, DSVI possibly should provide a preferable means for quantifying bulking.

A final comment on terminology and methodology in SVI-type measures perhaps is appropriate. As noted earlier, if the SVI test is conducted according to the procedure outlined in *Standard Methods* (since 1980) [i.e. with stirring] then SVI (*Sludge* Volume Index) and SSVI (Stirred *Specific* Volume Index) are one and the same thing. However, there appears to be a misconception that SVI and SSVI are different measures. This probably has arisen because SVI tests often continue to be performed according to the pre-1980 method without stirring. To avoid confusion it is suggested that the SVI test with and without stirring should be designated as sSVI and uSVI, respectively. The term sSVI itself may lead to confusion (with SSVI); however, this should not pose a problem as these are the same (aside from possible differences in the apparatus). This leads to a second point evident from the paper. Whenever SVI-type data are reported, the dimensions of the settling vessel also should be reported.

ACKNOWLEDGEMENTS

Credits: This study formed part of the activities of the Natural Sciences and Engineering Research Council (NSERC) / Wastewater Technology Centre Industrial Chair in Environmental Systems Engineering at McMaster University. The Support of the Chair sponsors is acknowledged.

Authors: Peter Dold is a Professor and Christopher Bye is a graduate student, in the Department of Civil Engineering, McMaster University. Correspondence should be addressed to Peter Dold, Department of Civil Engineering, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4L7, Canada.

REFERENCES

Daigger G.T. and Roper R.E. (1985) The relationship between SVI and activated sludge settling characteristics. *Journal WPCF*, **57**, 859-866.

Daigger G.T. (1995) Development of refined clarifier operating diagrams using an updated settling characteristics database. *Water Environment Research*, **67**, 95-100.

Dick R.I. and Vesilind P.A. (1969) The sludge volume index - what is it? *Journal WPCF*, **41**, 1285-1291.

Ekama G.A. and Marais G.v.R. (1984) Two improved activated sludge settleability measures. *IMIESA*, **9**, 20-27.

Ekama G.A. and Marais G.v.R. (1986) Sludge settleability and secondary settling tank design procedures. *Wat. Pollut. Control (G.B.)*, **87**, 101-113.

Härtel L. and Pöpel H.J. (1992) A dynamic secondary clarifier model including processes of sludge thickening. *Wat. Sci. Tech.*, **25**, 267-284.

Koopman B. and Cadee K. (1983) Prediction of thickening capacity using diluted sludge volume index. *Water Research*, **17**, 1427-1431.

Ozinsky A.E. and Ekama G.A. (1995) Secondary settling tank modelling and design Part 2: Linking sludge settleability measures. *Water SA*, **21**, 333-350.

Pitman A.R. (1984) Settling of nutrient removal activated sludges. *Wat. Sci. Tech.*, **17**, 493-504.

Sekine T., Tsugura H., Urushibara S., Furuya N., Fujimoto E. and Matsui S. (1989) Evaluation of settleability of activated sludge using a sludge settling analyzer. *Water Research*, **23**, 361-367.

Standard Methods for the Examination of Water and Wastewater 15th ed. (1980). American Public Health Association, Washington, D.C., 20005, USA.

Wahlberg E.J. and Keinath T.M. (1988) Development of settling flux curves using SVI. *Journal WPCF*, **60**, 2095-2100.

White M.J.D. (1976) Design and control of secondary settlement tanks. *Wat. Pollut. Control*, **75**, 459-467.

CHAPTER FOUR

EVALUATION OF CORRELATIONS FOR ZONE SETTLING VELOCITY PARAMETERS BASED ON SVI-TYPE MEASURES AND CONSEQUENCES IN SETTLING TANK DESIGN

This chapter contains the complete text of a paper published in *Water Environment Research*. The full reference is:

Bye C. M. and Dold P. L. (1999) Evaluation of correlations for zone settling velocity parameters based on sludge volume index-type measures and consequences in settling tank design, *Water Environment Research*, 71, 1333-1344.

EVALUATION OF CORRELATIONS FOR ZONE SETTLING VELOCITY PARAMETERS BASED ON SVI-TYPE MEASURES AND CONSEQUENCES IN SETTLING TANK DESIGN

Christopher M. Bye and Peter L. Dold

ABSTRACT

Determining zone settling velocity (ZSV) parameters for use in flux theory analysis (design or operating charts) is time consuming. Correlations have been proposed for these parameters based on more readily obtained SVI-type measures. A number of these correlations are reviewed, and their ability to predict ZSV parameters is evaluated. This assessment uses a model to generate SVI values from specified ZSV parameters. The SVI values are applied in correlations to generate predicted ZSV parameters which are compared to the specified ZSV parameters. The specified and correlation-generated ZSV parameters are used in the flux theory design procedure to assess the difference in maximum allowable overflow rate.

Key words: settleability, flux theory, zone settling velocity, SVI, DSVI, SSVI.

INTRODUCTION

Solids-flux theory often is used in the design and control of secondary settling tanks in suspended growth activated sludge systems. Application of this theory requires a relationship between biosolids zone settling velocity (ZSV) and concentration. This relationship regularly is described using the Vesilind equation (Dick and Vesilind, 1969). The semi-logarithmic equation relates the zone (hindered) settling velocity, V_S, of activated sludge to its concentration, X, and takes the following form:

$$V_S = V_0 \, e^{-KX} \tag{1}$$

where V_0 and K are empirical parameters. To determine these parameters for a given biosolids sample, it is necessary to perform several column settling tests over a range of suspended solids concentrations. This procedure seldom is carried out in practice because it is time-consuming and requires specialized equipment. In practice, more readily measurable parameters such as Sludge Volume Index (SVI) [or related parameters such as diluted SVI (DSVI)] are used to monitor biosolids settleability.

An approach which merges the benefits of flux theory analysis with the simplicity of SVI-type measures is to correlate the SVI-type measure with the ZSV *versus* X function parameters (i.e. V_0 and K in Eq. 1). In design of settling tanks, an SVI (or DSVI or $SSVI_{3.5}$) value is assumed, a correlation is used to estimate V_0 and K, and these values are applied in flux theory analysis to determine a maximum allowable overflow rate. For operations, a correlation is applied using the measured SVI, and the estimated V_0 and K values are used to assess the operating condition (principally settler underflow recycle rate) in an operating chart based on flux theory.

Bye and Dold (1998) identified a number of problems with SVI-type measures which in turn question the approach of correlating V_0 and K to SVI-type measures:

1. Depending on the test conditions (column height, biosolids settleability and compactability), SVI may show a marked dependence on the biosolids concentration. Cases were observed where the SVI changed by a factor of three

over a solids concentration range of only 2 g/L. That is, a sample with given zone settling parameters (V_0 and K) can exhibit a wide range of SVI values even for small variations in concentration in the test. Depending on the concentration at which SVI is measured, a correlation based on SVI may predict widely different pairs of V_0 and K values.

2. The DSVI test "forces" the SVI test conditions into the region where SVI is independent of solids concentration. Intuitively it may seem that this is a suitable measuring state. However, in this region the observed SVI bears no relation to the settleability of the test sample. Rather, the DSVI provides a measure of biosolids compactability. That is, two samples with very different zone settling parameters (V_0 and K) may have the same DSVI. However, a correlation based on DSVI would predict the same V_0 and K for each sample.

3. Mathematically, it seems dubious that two parameters from a model such as Eq. 1 which quantifies how solids concentration (X) influences ZSV can be estimated based on a single SVI value from a test conducted at a single X value.

The objectives of this paper are to:

1. Evaluate the various correlations by comparing predicted V_0 and K values to "true" V_0 and K values. The model developed by Bye and Dold (1998) is used to generate SVI *versus* biosolids concentration profiles over a range of biosolids concentrations for selected "true" V_0 and K pairs (see Appendix). A minimum and a maximum SVI value for each V_0 and K pair are identified from the profile. These SVI values are then used in correlations to estimate V_0 and K pairs, which are then compared with the "true" V_0 and K.

2. Assess the difference in maximum allowable settling tank overflow rate when applying the flux theory design procedure based on the "true" or the correlation-generated ZSV parameters.

BACKGROUND

Bye and Dold (1998) developed a mechanistic model to simulate the behaviour observed in a settling test; that is, the changing interface height with time (see Appendix). Three parameters must be specified; these are: (1) test column height, H_0, (2) maximum biosolids compactability, X_M, and (3) a pair of Vesilind parameters, V_0 and K. In practice, a short lag phase may be observed at the start of the test, while biosolids flocculate and the defined interface forms. In this case, a short time delay term, t_F, can be included in the model. Simulating a settling test for a given initial biosolids concentration allows the SVI to be calculated based on the interface height at 30 minutes. A large number of settling tests can be simulated for a range of initial solids concentrations to determine the 30-minute settled volume for each concentration (Figure 4.1 shows plots for four concentrations). The data in turn can be used to generate the SVI *versus* Solids Concentration profile (see example in Figure 4.2). The trend in SVI predicted by the model consists of three distinct sections. For low solids concentrations the SVI is constant with increasing concentration; this corresponds to the DSVI. This section is followed by a rapid increase in SVI with further increase in concentration up to a maximum value. Finally, the SVI decreases with further increase in concentration, and follows a boundary contour corresponding to the case where no settling has occurred in the test.

An example of the predicted variation of SVI with solids concentration is shown in Figure 4.2 together with measured SVI values. Figure 4.2 was generated from a series of stirred column settling tests conducted simultaneously on one mixed liquor sample over a range of biosolids concentrations. Interface height *versus* time data were collected for each column test, and the initial solids concentrations in each column were measured. Each SVI value shown in Figure 4.2 was calculated from the settled volume observed at 30 minutes in each column. The V_0 and K values reported in Figure 4.2 are not hypothetical. Rather, these were calculated from a semi-logarithmic plot of Eq. 1 using the zone settling velocity measurements for each column test. This pair of V_0 and K values was then applied in the model of Bye and Dold (1998) to generate the SVI predictions shown as a solid line in Figure 4.2 [The reported SVI values measured in various settling vessels for this sludge sample were: 103 mL/g (1.73 m tall stirred settling column), 58.2 mL/g (1 L stirred graduated cylinder), 67.9 mL/g (2 L stirred settleometer), 76.2 mL/g (1 L graduated cylinder without stirring), 70.7 (2 L settleometer without stirring)].

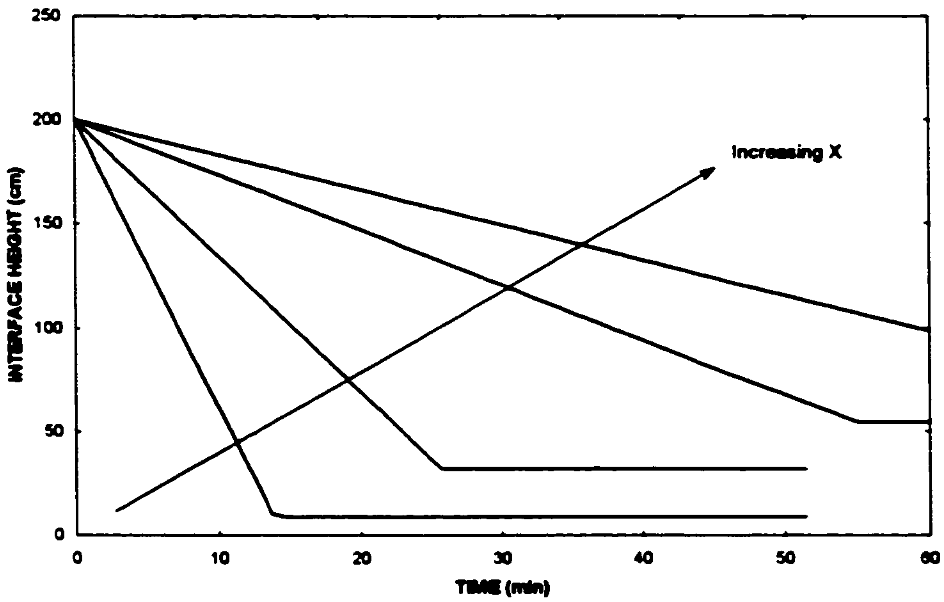

Figure 4.1: Simulation of settling tests over a range of solids concentrations.

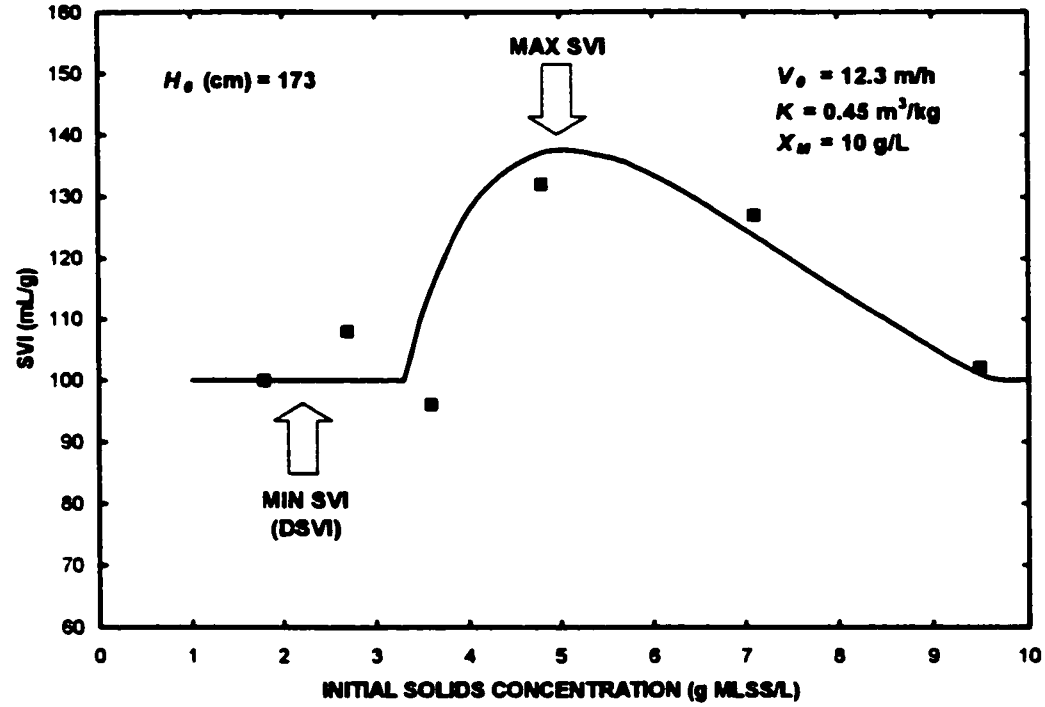

Figure 4.2: Simulated SVI *versus* Solids Concentration profile (solid line) compared to measured data.

The model is a useful tool to explain the observed variability of SVI-type measures with solids concentration. Also, it provides a means to demonstrate how various test conditions such as column height and biosolids compactability impact the measurement of SVI. These aspects are discussed by Bye and Dold (1998).

In this paper the model is used as a means to generate SVI (and DSVI) values to use in the evaluation of various correlations for V_0 and K from SVI-type measures. To evaluate the correlations, the following procedure was developed:

- For a given biosolids sample it was assumed that the Vesilind parameters V_0 and K were known (referred to as the "true" V_0 and K). The model was used to generate an SVI - Solids Concentration profile such as the one shown in Figure 4.2 for this "true" V_0 and K pair. The plot of SVI *versus* X_0 is a continuous function. However, for the purposes of this evaluation, the values of interest from the SVI - Solids Concentration profile were (1) the maximum SVI, and (2) the minimum SVI (at the low concentration range), which is also the DSVI (Bye and Dold, 1998 and Appendix).

- The minimum SVI (i.e. DSVI) and maximum SVI values obtained from the model using the "true" V_0 and K pair were used in the correlations to predict pair(s) of V_0 and K values. It should be noted that certain correlations are based on DSVI specifically; these yield one pair of predicted V_0 and K values. However, correlations based on SVI were used to generate two V_0 and K pairs; one pair corresponding to the maximum SVI and the other corresponding to the minimum SVI.

- The "true" and predicted V_0 and K values were applied in the flux theory design procedure outlined by the IAWQ (Ekama *et al.*, 1997) to obtain estimates of maximum allowable settling tank overflow rates for different feed concentrations.

SUMMARY OF CORRELATIONS

Table 4.1 summarizes a number of relationships proposed for relating various SVI-type settleability measures to the Vesilind parameters V_0 and K. Koopman and Cadee (1983) related both V_0 and K as functions of the DSVI, using data obtained from earlier studies. Pitman (1984) developed a relationship between the quotient V_0/K and $SSVI_{3.5}$, as well as a relationship between V_0/K and SVI, using data obtained over a period of six years at four full-scale nutrient removal plants. The SVI relationship was found to exhibit a poor fit to available data. Based on Pitman's data, Ekama and Marais (1986) proposed a relationship between K and the quotient V_0/K that could be used to separate the two parameters. Daigger and Roper (1985) used data from six pilot-scale and two full-scale conventional activated sludge plants to obtain a relationship between the parameter K and SVI, treating V_0 as a constant. Wahlberg and Keinath (1988) used data from twenty-one full-scale plants to evaluate four proposed correlations to estimate V_0 and K as separate functions of "stirred" SVI. Catunda and van Haandel (1992) proposed relationships for V_0, K, $SSVI_{3.5}$, and DSVI which depended upon the active biosolids fraction. Daigger (1995) updated his earlier relationships using an expanded database. Ozinsky and Ekama

(1995) used a rigorous statistical approach to separate a large database into subsets, and proposed a number of correlations for V_0 and K based on SVI, DSVI and $SSVI_{3.5}$ for each subset. Sekine *et al.* (1989) and Härtel and Pöpel (1992) are further examples of using correlations for V_0 and K based on SVI-type measures. The correlation approach seems to have gained quite wide acceptance.

Table 4.1: Proposed correlations for relating V_0 and K to various SVI-type settleability measures

Reference	Correlation For V_0 (m/h)	Correlation For K (m^3/kg)
Koopman and Cadee (1983)	$\ln(V_0) = 2.605 - 0.00365 * DSVI$	$K = 0.249 + 0.002191 * DSVI$
Pitman (1984)	$\frac{V_0}{K} = 67.9e^{-0.016SSVI_{3.5}}$ (kg/m^{2}h)	
Ekama and Marais (1986)		$K = 0.88 - 0.393 * \log\left(\frac{V_0}{K}\right)$
Daigger and Roper (1985)	$V_0 = 7.80$	$K = 0.148 + 0.00210 * SVI$
Wahlberg and Keinath (1988)	$V_0 = 15.3 - 0.0615 * sSVI$	$K = 0.426 - 0.00384 \cdot sSVI + 0.0000543 \cdot sSVI^2$
Härtel and Pöpel (1992)	$V_0 = 17.4e^{-0.0113SVI} + 3.931$	$K = 1.043 - 0.9834e^{-0.00581SVI}$
Catunda and van Haandel (1992)	$V_0 = 12.0 - 3\left(\frac{SSVI_{3.5} - 43}{25}\right)$	$K = 0.30 + 0.08\left(\frac{SSVI_{3.5} - 43}{25}\right)$
	$V_0 = 12.0 - 3\left(\frac{DSVI - 43}{50}\right)$	$K = 0.30 + 0.08\left(\frac{DSVI - 43}{50}\right)$
Daigger (1995)	$V_0 = 6.495$	$K = 0.1646 + 0.001586 * SVI$
	$V_0 = 7.973$	$K = 0.0583 + 0.00405 * SSVI_{3.5}$
	$V_0 = 7.599$	$K = 0.1030 + 0.002555 * DSVI$
Ozinsky and Ekama (1995)	$V_0 = 8.53094e^{-0.00165 * SVI}$	$K = 0.20036 + 0.00091 * SVI$
	$V_0 = 11.59936e^{-0.00636 * SSVI_{3.5}}$	$K = 0.15128 + 0.00287 * SSVI_{3.5}$
	$V_0 = 6.35543e^{-0.00084 * DSVI}$	$K = 0.19818 + 0.00123 * DSVI$

PREDICTION OF ZSV PARAMETERS

To evaluate the ability of the correlations to predict V_0 and K values, the model proposed by Bye and Dold (1998) was applied to two biosolids samples with different assumed settling characteristics ("poor" and "good"). That is, two sets of "true" V_0 and K pairs were applied in the model to generate SVI values. The SVI values were then substituted in the correlations to predict V_0 and K values to compare to the "true" values. The procedure for one "true" V_0 and K pair, one column height (H_0), and one maximum compactability (X_M) is shown in the diagram below:

The first sample was representative of a "poor" settling biosolids sample with ZSV parameters V_0 and K of 7.2 m/h and 0.40 m^3/kg, respectively. These values were applied in the model for two column heights (H_0 = 50 and 200 cm) and two biosolids maximum compactabilities (X_M = 10 and 20 g/L). This generated four SVI *versus* Solids Concentration plots (e.g. Figure 4.2), each with a maximum SVI and a minimum SVI (i.e. DSVI). In the case of this "poor" settling biosolids sample, the predicted SVI values ranged from 50 to 160 mL/g (with a DSVI range of 50 to 100 mL/g). These results are summarized in Table 4.2. Both the minimum and maximum SVIs were applied in the correlations based on SVI proposed by Wahlberg and Keinath (1988), Daigger (1995), and Ozinsky and Ekama (1995). The DSVI values were applied in the correlations based on DSVI proposed by Daigger (1995) and Ozinsky and Ekama (1995). This resulted in the pairs of predicted V_0 and K values listed in Table 4.3.

The evaluations also were performed for a biosolids sample exhibiting "good" settling characteristics, with ZSV parameters V_0 and K of 9.6 m/h and 0.30 m^3/kg, respectively. Again, these were applied in the model of Bye and Dold (1998) for the same two column heights (H_0 = 50 and 200 cm) and two biosolids maximum compactabilities (X_M = 10 and

20 g/L). This generated another set of four SVI *versus* Solids Concentration plots, each with a maximum SVI and a minimum SVI (i.e. DSVI). In the case of the "good" settling biosolids sample, the predicted SVI values ranged from 50 to 101 mL/g (with a DSVI range of 50 to 100 mL/g). These results are summarized in Table 2. It is evident that the model demonstrates less SVI variability with concentration as a result of the improved settling qualities of the biosolids sample in this simulation. Once again, the minimum and maximum SVIs were applied in the correlations based on SVI proposed by Wahlberg and Keinath (1988), Daigger (1995), and Ozinsky and Ekama (1995). The DSVI values were applied in the correlations based on DSVI proposed by Daigger (1995) and Ozinsky and Ekama (1995). This resulted in the pairs of predicted V_0 and K values listed in Table 4.4.

Table 4.2: Ranges of SVI and DSVI values from analysis for two column heights and two maximum solids compactabilities.

Poor Settling Sludge	SVI	50 – 160 mL/g
	DSVI	50 – 100 mL/g
Good Settling Sludge	SVI	50 – 101 mL/g
	DSVI	50 – 100 mL/g

Table 4.3: ZSV parameter predictions for "poor" settling sludge [V_0 = 7.2 m/h, K = 0.40 m^3/kg (r^2 values in brackets)].

	H_0 (cm)	X_M (g/m^3)	Wahlberg & Keinath$_{SVI}$		Daigger$_{SVI}$		Ozinsky & Ekama$_{SVI}$		Ozinsky & Ekama$_{DSVI}$		Daigger$_{DSVI}$	
			V_0	K	V_0	K	V_0	K	V_0	K	V_0	K
Based On SVI_{MAX}	50	10	9.2	0.59	6.5	0.32	7.2	0.29	[redacted]			
			(0.754)		(0.851)		(0.496)					
		20	9.8	0.51	6.5	0.31	7.4	0.28				
			(0.888)		(0.735)		(0.292)					
	200	10	5.5	1.20	6.5	0.42	6.6	0.35				
			(-)		(0.975)		(0.958)					
		20	5.2	1.20	6.5	0.42	6.6	0.35				
			(-)		(0.984)		(0.942)					
Based On SVI_{MIN}	50	10	9.2	0.59	6.5	0.32	7.2	0.29	5.8	0.32	7.6	0.36
			(0.754)		(0.851)		(0.496)		(0.905)		(0.938)	
		20	12.2	0.37	6.5	0.24	7.9	0.25	6.1	0.26	7.6	0.23
			(0.857)		(-)		(-)		(0.096)		(-)	
	200	10	9.2	0.59	6.5	0.32	7.2	0.29	5.8	0.32	7.6	0.36
			(0.754)		(0.851)		(0.496)		(0.905)		(0.938)	
		20	12.2	0.37	6.5	0.24	7.9	0.25	6.1	0.26	7.6	0.23
			(0.857)		(-)		(-)		(0.096)		(-)	

Table 4.4: ZSV parameter predictions for "good" settling sludge [$V_0 = 9.6$ m/h, $K = 0.30$ m^3/kg (r^2 values in brackets)].

	H_0 (cm)	X_M (g/m^3)	Wahlberg & Keinath$_{SVI}$		Daigger$_{SVI}$		Ozinsky & Ekama$_{SVI}$		Ozinsky & Ekama$_{DSVI}$		Daigger$_{DSVI}$	
			V_0	K	V_0	K	V_0	K	V_0	K	V_0	K
Based On SVI$_{MAX}$	50	10	9.2	0.59	6.5	0.32	7.2	0.29	[redacted]			
			(0.118)		(0.762)		(0.932)					
		20	11.5	0.40	6.5	0.26	7.7	0.26				
			(0.823)		(0.976)		(0.963)					
	200	10	9.1	0.59	6.5	0.32	7.2	0.29				
			(0.109)		(0.762)		(0.932)					
		20	9.1	0.59	6.5	0.32	7.2	0.29				
			(0.075)		(0.903)		(0.987)					
Based On SVI$_{MIN}$	50	10	9.2	0.59	6.5	0.32	7.2	0.29	5.8	0.32	7.6	0.36
			(0.118)		(0.762)		(0.932)		(0.640)		(0.753)	
		20	12.2	0.37	6.5	0.24	7.9	0.25	6.1	0.26	7.6	0.23
			(0.922)		(0.917)		(0.919)		(0.975)		(0.795)	
	200	10	9.2	0.59	6.5	0.32	7.2	0.29	5.8	0.32	7.6	0.36
			(0.118)		(0.762)		(0.932)		(0.640)		(0.753)	
		20	12.2	0.37	6.5	0.24	7.9	0.25	6.1	0.26	7.6	0.23
			(0.922)		(0.917)		(0.919)		(0.975)		(0.795)	

Inspection of Tables 4.3 and 4.4 shows that (1) there are significant differences between the predicted V_0 and K values from the different correlations; and (2) the predicted values generally are not in good agreement with the "true" values. However, differences in V_0 and differences in K are difficult to interpret and are not of any particular relevance. Of more importance is how accurately the ZSV is predicted over a range of biosolids concentrations when the pairs of parameter values are applied in the Vesilind equation and compared to the "true" ZSV. Sample graphical representations of this comparison are shown in Figures 4.3 and 4.4. These compare the ZSV (logarithmic scale) using the predicted V_0 and K pairs in the Vesilind equation to the "true" ZSV. That is, the plots are presented in the form of the linear transformation of the Vesilind equation that commonly is used to obtain V_0 and K pairs from measured data. Figure 4.3 shows a case where the fit is relatively good, while Figure 4.4 shows a case where the fit is poor. The predicted ZSV values tend to either straddle the "true" values for a given case or are all above or below the "true". [Note that a difference of one unit on the logarithmic scale corresponds to a 2.7 times difference in ZSV].

In an effort to provide a numerical comparison of the goodness of fit, r^2 values between the predicted and "true" ZSV were calculated. These r^2 values were computed from the linear plots such as Figures 4.3 and 4.4. This number represents how well (or poorly) the predicted ZSV fits the "true" ZSV over the given range of solids concentrations. Tables 4.3 and 4.4 show r^2 values for each V_0 and K pair (in parentheses below the correlation values). Examination of the r^2 values again confirms that the ZSV obtained via the correlations generally is not in good agreement with the "true" ZSV. Inspection of r^2 values in any row of the tables indicates that there is poor agreement between the different correlations. Inspection of the r^2 values in columns of the tables shows a wide variation in predictive capacity for each correlation depending on the conditions for measuring SVI. A general observation from the results is that r^2 values closer to unity are obtained when the predicted K is closer to the "true" K.

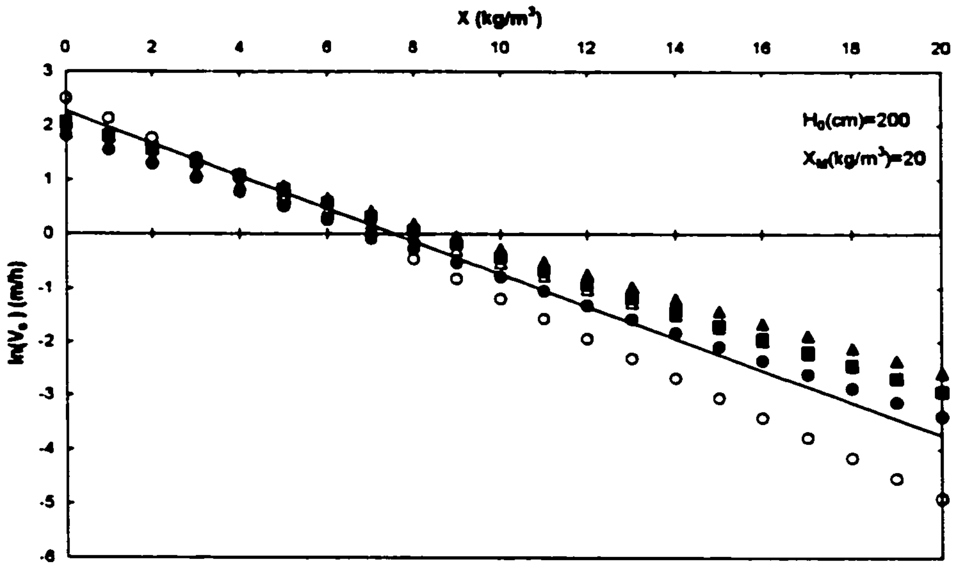

Figure 4.3: Effect of using V_0 and K pairs predicted from minimum SVI (i.e. DSVI) to estimate settling velocity for a "good" settling sludge (—- "True", O - Wahlberg & Keinath$_{SVI}$, Δ - Daigger$_{SVI}$, ■ - Ozinsky & Ekama$_{SVI}$, ● - Ozinsky & Ekama$_{DSVI}$, ▲ - Daigger$_{DSVI}$).

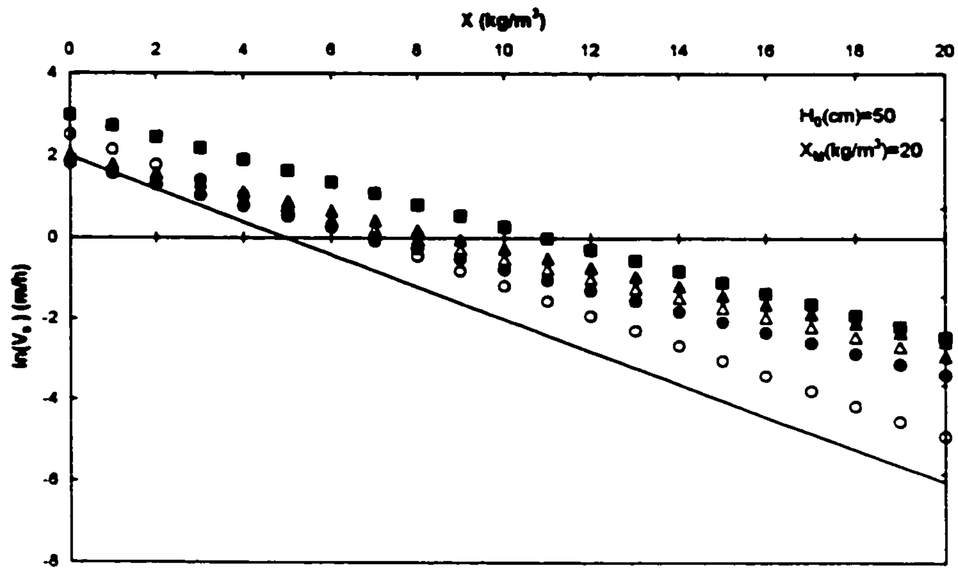

Figure 4.4: Effect of using V_0 and K pairs predicted from minimum SVI (i.e. DSVI) to estimate settling velocity for a "poor" settling sludge (—- "True", O - Wahlberg & Keinath$_{SVI}$, Δ - Daigger$_{SVI}$, ■ - Ozinsky & Ekama$_{SVI}$, ● - Ozinsky & Ekama$_{DSVI}$, ▲ - Daigger$_{DSVI}$).

IMPACT ON SETTLER DESIGN

In the previous section maximum SVI values and minimum SVI values (equivalent to DSVI) were generated for (1) "true" V_0 and K values (representing either good/poor settleability); (2) two settling column heights (50 or 200 cm); and (3) two biosolids compactabilities (10 or 20 g/L). Table 2 summarizes the ranges of SVI and DSVI values. These minimum and maximum SVI and DSVI values, in turn, were applied in various correlations to generate predicted V_0 and K values listed in Tables 4.3 and 4.4.

The objective in this section is to compare secondary settling tank design and operation based on predicted V_0 and K values to that based on "true" V_0 and K values. The approach for the comparison is as follows:

1. Apply each minimum and maximum SVI (or DSVI) value from Table 2 in each correlation to provide predicted V_0 and K values.

2. Apply each pair of predicted V_0 and K values to determine the maximum allowable overflow rate, Qi/A (i.e. the minimum settling tank area for a given influent flow) based on flux theory analysis (see below) for three different feed concentrations, X_0 (1200, 2400, 3600 mg/L) that are representative of the range of typical activated sludge bioreactor concentrations.

3. Compare predictions to Qi/A for "true" V_0 and K (for each X_0).

Figure 4.5a shows the IAWQ design and operation chart (Ekama *et al.*, 1997) that was used to calculate maximum allowable Qi/A values for different settling tank feed concentrations.

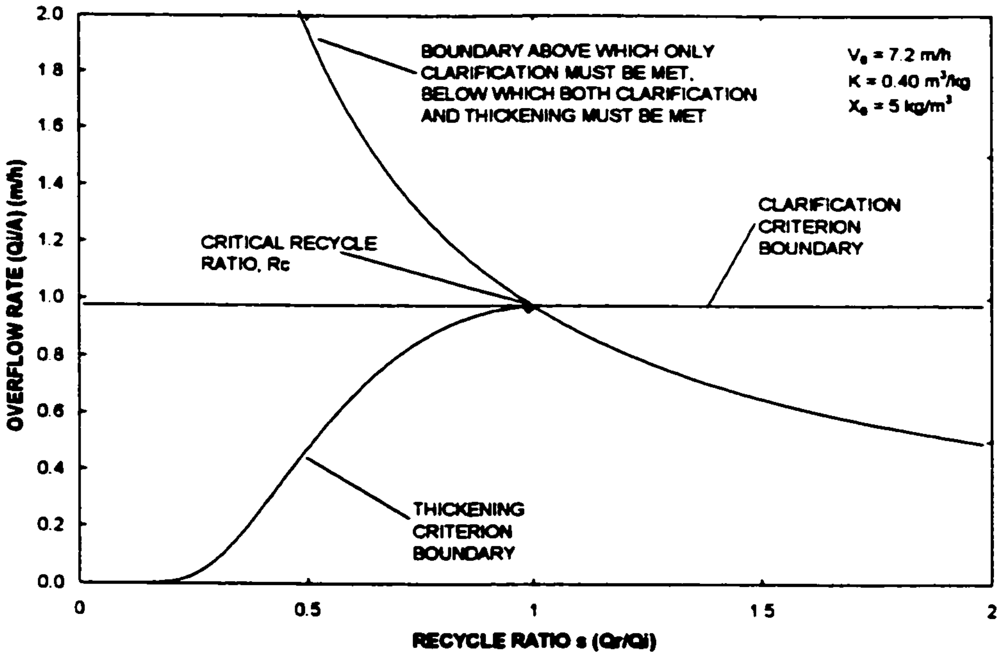

Figure 4.5a: Design and operating chart for high feed concentration.

The maximum allowable overflow rate *Qi/A* for a given feed concentration and biosolids settling characteristics is found at the critical recycle ratio, R_C, which satisfies the thickening *and* clarification criteria shown in Figure 4.5a (R_C is the maximum possible underflow recycle ratio within thickening criterion constraints). It should be noted that in the case of lower feed concentrations, the thickening and clarification boundary lines do not necessarily intersect on the hyperbola defining regions where design is either thickening-and/or clarification-controlled. An example is shown in Figure 4.5b. At low feed concentrations, selecting overflow rate *Qi/A* corresponding to R_C will result in violation of the clarification criterion. In this case, the maximum allowable overflow rate that satisfies *both* the thickening and clarification criteria is found at a lower recycle ratio, shown in Figure 4.5b as the "Design Point" [For a detailed explanation of the design and operating chart, refer to Appendix 2].

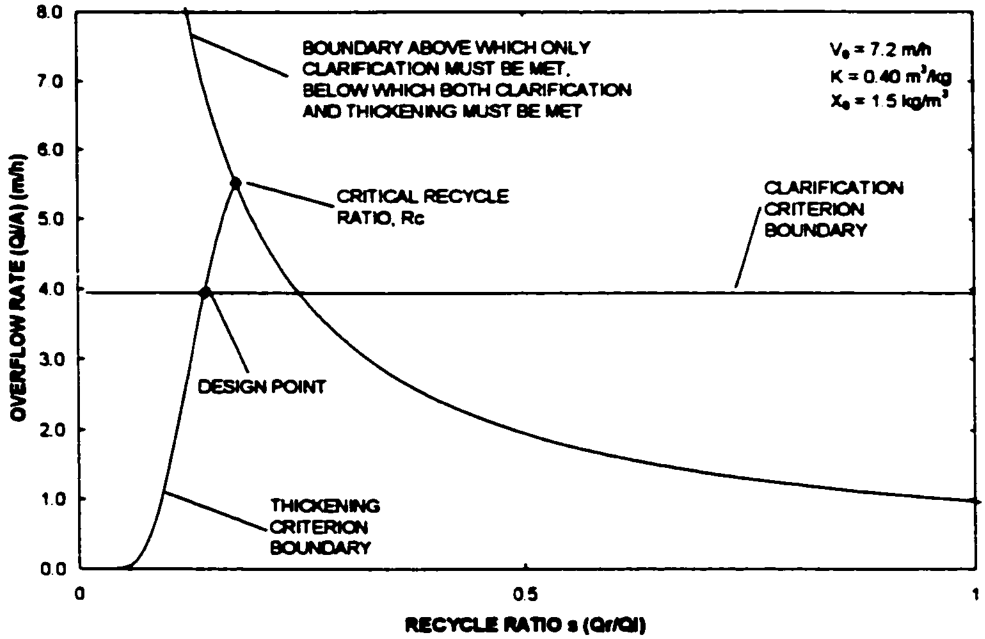

Figure 4.5b: Design and operating chart for low feed concentration.

The predicted minimum and maximum SVI (50 and 160 mL/g) of the "poor" settling biosolids sample (see Table 2) were applied in three SVI correlations of Wahlberg and Keinath (1988), Daigger (1995), and Ozinsky and Ekama (1995). This resulted in six pairs of V_0 and K values that were used in the settler design procedure to determine the corresponding maximum allowable overflow rate for each. Figure 4.6 compares these Qi/A values to the Qi/A for the "true" V_0 and K. The Figure shows three groups of bars, corresponding to the three different settler feed concentrations (1.2, 2.4, and 3.6 kg/m^3).

The same procedure was followed to generate the data for Figure 4.7. However, this case was based on the "good" settling biosolids.

This approach also was applied with the DSVI data in Table 4.2, using the two DSVI correlations of Daigger (1995) and Ozinsky and Ekama (1995). The results are presented in Figures 4.8 and 4.9.

Inspection of Figures 4.6 to 4.9 identifies that:

- There can be significant differences between "true" and predicted maximum allowable overflow rates.
- There can be significant differences from correlation to correlation.

The data presented in this section were generated by selecting specific SVI values (from a continuum of SVI-Concentration) and for two sets of ZSV parameters "poor" and "good" settling). Therefore it would not be appropriate to draw general conclusions about the merits or demerits of the different correlations. Rather, the objective has been to demonstrate a practical (i.e. design-related) consequence of the underlying fact that correlations for ZSV parameters (V_0 and K) based on SVI-type measures may provide poor estimates.

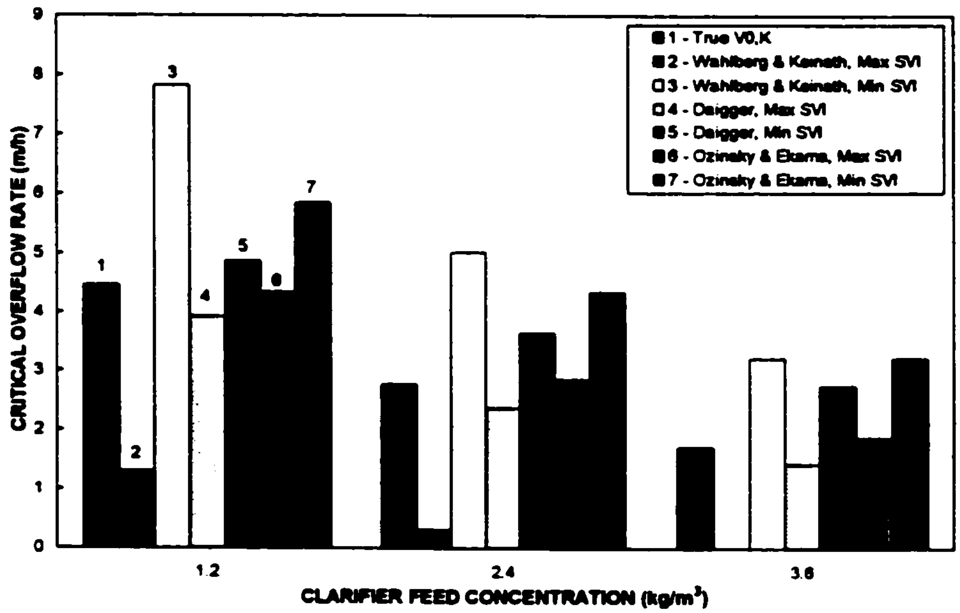

Figure 4.6: Comparison of predicted and "true" maximum overflow rates for SVI correlations for "poor" settling biosolids.

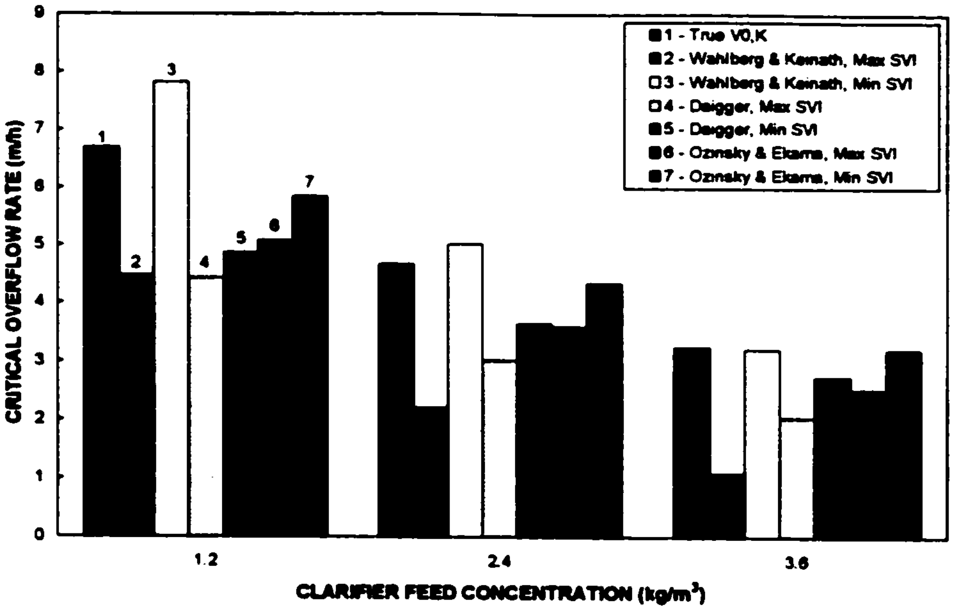

Figure 4.7: Comparison of predicted and "true" maximum overflow rates for SVI correlations for "good" settling biosolids.

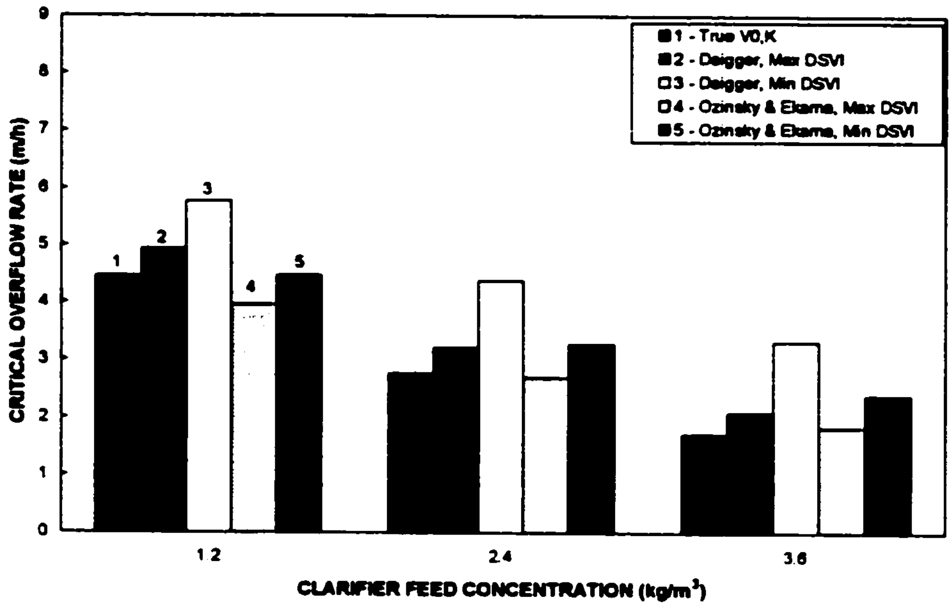

Figure 4.8: Comparison of predicted and "true" maximum overflow rates for DSVI correlations for "poor" settling biosolids.

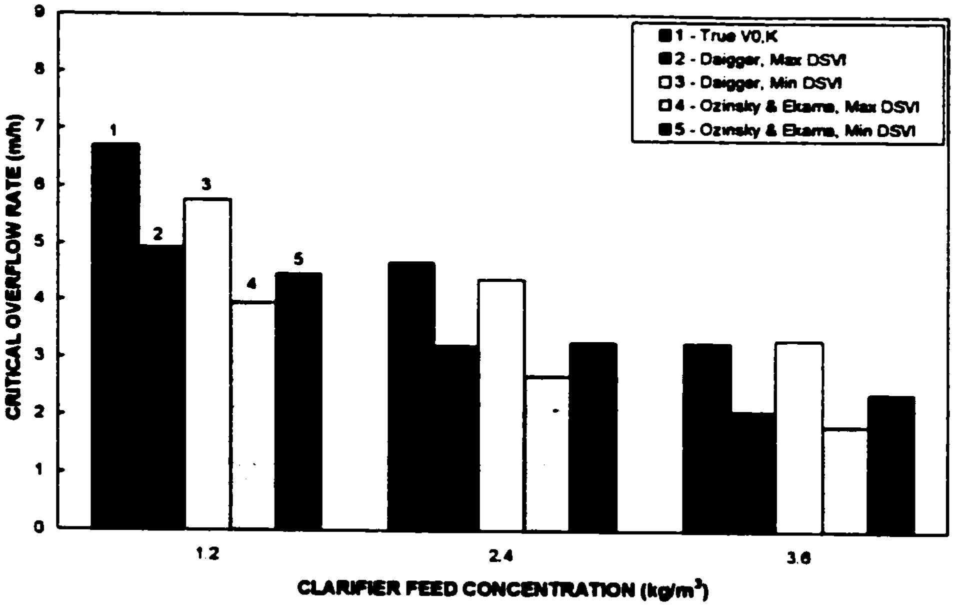

Figure 4.9: Comparison of predicted and "true" maximum overflow rates for DSVI correlations for "good" settling biosolids.

CONCLUSIONS

The model of Bye and Dold (1998) for simulating the settling behaviour in a hindered settling test has been used as a basis for evaluating proposed correlations for estimating zone settling velocity parameters based on SVI-type measures. The overall conclusions from the comparison is that (1) there are significant differences between the predicted V_0 and K values from the different correlations; and (2) the predicted values generally are not in good agreement with the "true" values. The ZSV obtained via the correlations generally is not in good agreement with the "true" ZSV, and there is a wide variation in predictive capacity for each correlation depending on the conditions for measuring SVI. A consequence of differences between predicted and "true" ZSV parameters when applied in flux theory analysis is significant differences in maximum allowable overflow rate.

The purpose of this analysis has not been to "damn" either the correlations or SVI as a measure of sludge settleability. Undoubtedly SVI will continue to be a very useful indicator in plant operations. The objective has been to bring out the underlying problems regarding SVI-type measures. For example, for a given biosolids sample:

- SVI can change significantly with concentration, even for relatively small concentration differences;
- The settling column height impacts the SVI. This is not through impacting settleability *per se*; rather, it is merely a calculation artifact.
- DSVI is not impacted by column height. However, DSVI is determined by biosolids compactability and does not relate to settling rate directly. That is, samples with different settling characteristics may have the same DSVI.

The result of these factors is that the database of information on SVI-type measures is not consistent. For example, a set of SVI measures in a 1 L cylinder cannot be compared to SVI results from tests conducted in 6 foot settling columns. This likely is a reason why Ozinsky and Ekama (1995) found that certain sets of data from different researchers could not be pooled on a statistical basis.

Given these problems, it is not surprising that there are such large differences between different correlations and that correlations differ for different SVI measuring conditions (column height, etc.). Nevertheless, it is still questionable whether correlations will ever provide a reliable tool for predicting ZSV parameters. How can a measure at one concentration tell us how concentration influences settleability? Irrespective of this, the need has been identified to stress a consistent set of conditions for measuring SVI, as well as reporting the concentration, if values are to be compared.

ACKNOWLEDGEMENTS

Credits: This study was funded in part by a grant from the Canadian Natural Sciences and Engineering Research Council (NSERC).

Authors: Peter Dold is an Adjunct Professor and Christopher Bye is a graduate student, in the Department of Civil Engineering, McMaster University. Correspondence should be addressed to Peter Dold, Department of Civil Engineering, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4L7, Canada.

REFERENCES

Bye C M and Dold P L (1998) Sludge volume index settleability measures: effects of solids characteristics and test parameters. *Water Environment Research*, **70**, 87-93.

Catunda P.F.C. and van Haandel A.C. (1992) Activated sludge settling part I: Experimental determination of activated sludge settleability. *Water SA*, **18**, 165-172.

Daigger G.T. and Roper R.E. (1985) The relationship between SVI and activated sludge settling characteristics. *Journal WPCF*, **57**, 859-866.

Daigger G.T. (1995) Development of refined clarifier operating diagrams using an updated settling characteristics database. *Water Environment Research*, **67**, 95-100.

Dick R.I. and Vesilind P.A. (1969) The sludge volume index - what is it? *Journal WPCF*, **41**, 1285-1291.

Ekama G.A., Barnard J.L., Günthert F.W., Krebs P., McCorquodale J.A., Parker D.S., and Wahlberg E.J. (1997) Secondary settling tanks: theory, modelling, design and operation. *IAWQ Scientific and Technical Report No. 6*. International Association on Water Quality, London.

Ekama G.A. and Marais G.v.R. (1986) Sludge settleability and secondary settling tank design procedures. *Wat. Pollut. Control (G.B.)*, **87**, 101-113.

Härtel L. and Pöpel H.J. (1992) A dynamic secondary clarifier model including processes of sludge thickening. *Wat. Sci. Tech.*, **25**, 267-284.

Koopman B. and Cadee K. (1983) Prediction of thickening capacity using diluted sludge volume index. *Water Research*, **17**, 1427-1431.

Ozinsky A.E. and Ekama G.A. (1995) Secondary settling tank modelling and design Part 2: Linking sludge settleability measures. *Water SA*, **21**, 333-349.

Pitman A.R. (1984) Settling of nutrient removal activated sludges. *Wat. Sci. Tech.*, **17**, 493-503.

Sekine T., Tsugura H., Urushibara S., Furuya N., Fujimoto E., and Matsui S. (1989) Evaluation of settleability of activated sludge using a sludge settling analyzer. *Water Research*, **23**, 361-367.

Wahlberg, E.J., and Keinath, T.M. (1988) Development of settling flux curves using SVI. *Journal WPCF*, **60**, 2095-2100.

APPENDIX

This Appendix provides a detailed explanation of the material referenced in the Background section. Readers are directed to Bye & Dold (1998) for further explanation. A model was developed to assess the impact of variables in settling tests (column height, initial MLSS concentration, biosolids compactability, etc.). The model is based on three assumptions which identify three phases in the simulated settling test:

Phase 1: At the outset of the test there may be a period of reflocculation before sedimentation begins. This is modeled by the inclusion of a short "dead" time, t_F, during which no settlement occurs. If there is no lag phase at the start then t_F will be zero.

Phase 2: During sedimentation the downward velocity of the biosolids-water interface is governed by the Vesilind settling model. Applying this model, the linear change in interface height as a function of time is given by Eq. A1:

$$H(t) = H_0 - V_0\, e^{-KX_0}(t - t_F) \qquad \text{(A1)}$$

where H_0 is the initial height of the sample in the settling column, X_0 is the initial biosolids concentration, and $(t - t_F)$ is the time from the start of the sedimentation phase. The end of this linear phase of zone settling is determined by the biosolids compactability (see below).

Phase 3: It is assumed that, for a given mixed liquor, the final settled solids volume is directly proportional to the initial biosolids concentration. That is, a mixed liquor sample exhibits a certain maximum biosolids compactability, X_M (units of g/L). This assumption has been verified with data sets from a number of treatment plants; Figure 4.A1 presents an example data set. The maximum biosolids compactability, X_M, is obtained by taking the inverse of the slope of the line in Figure 4.A1. This assumption implies that Phase 1 continues until the biosolids interface has reached a point where the concentration of solids at the base of the column has attained the maximum compactability, X_M. From a mass balance, the final settled height in the column, H', is given by:

$$H' = \frac{X_0 H_0}{X_M}(m) \tag{A2}$$

A graphical representation of the simulated interface height in a settling test is shown in Figure 4.A2.

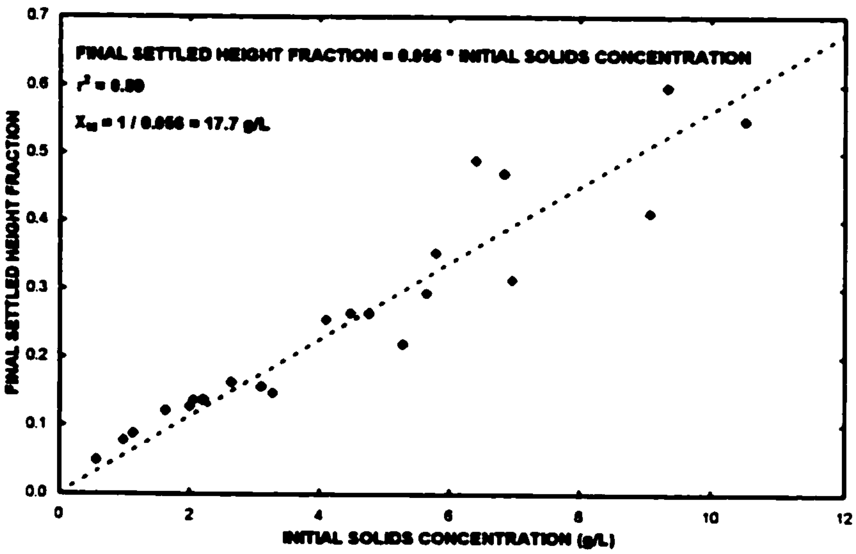

Figure 4.A1: Relationship between solids concentration and final settled height.

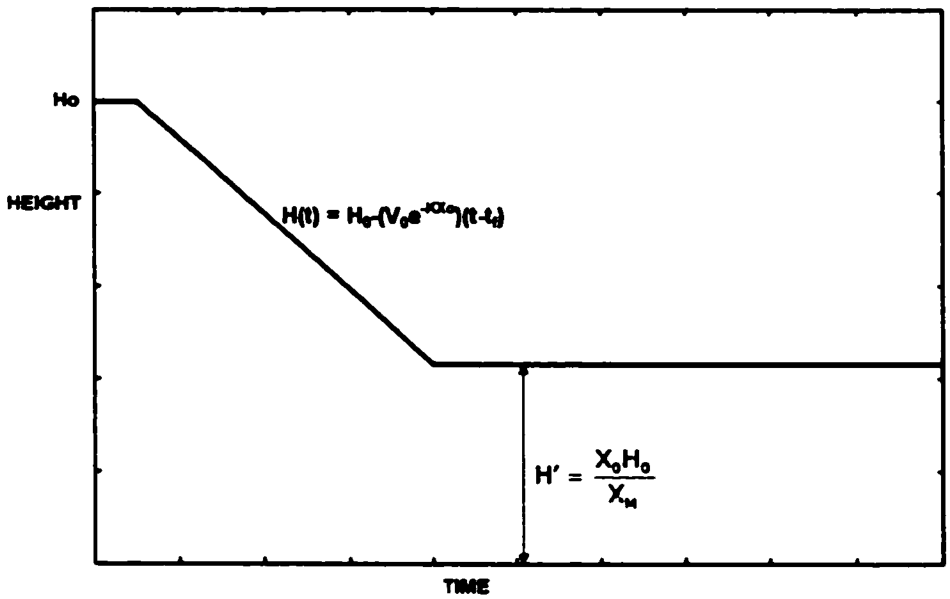

Figure 4.A2: Model used to generate settling profile.

The model can be used to generate an SVI *versus* Solids Concentration profile (such as the one shown in Figure 4.2) for a given biosolids sample by the following procedure. First, the biosolids settling parameters (V_0 and K), the biosolids compactability (X_M) and the settling column height (H_0) are specified. [If an initial lag phase is to be modeled t_F also must be specified]. The model then is applied to generate a series of solids interface height profiles for a range of solids concentrations. An example is shown for four solids concentrations in Figure 4.A3. Next, the SVI for each concentration is calculated by computing the fractional settled height at 30 minutes, dividing this value by the initial solids concentration X_0, and multiplying by 1000 to normalize to a one litre cylinder. Whether the "elbows" in Figure 4.A3 occur before or after 30 minutes is crucial in determining the shape of the SVI - Solids Concentration curve.

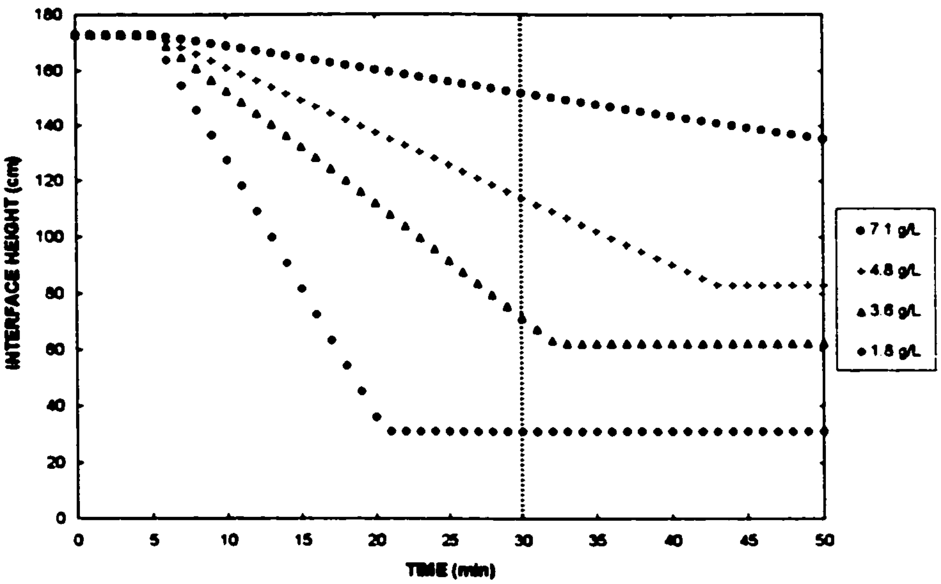

Figure 4.A3: Model application to biosolids sample at different concentrations.

If the biosolids interface has not reached the compacted height *H'* by 30 minutes (i.e. the "elbow" occurs after 30 minutes), the interface height is governed by Eq. A1. Therefore, the SVI is a function of the initial solids concentration and the zone settling parameters:

$$SVI = \left[\frac{H_0 - \left\{V_0\, e^{-KX_0}(0.5 - t_F)\right\}}{X_0 H_0}\right] 1000 \qquad \text{(A3)}$$

Equation A3 illustrates that the SVI during Phase 1 is a non-linear function of solids concentration for a given sample and test conditions.

If the biosolids interface has settled rapidly and reached the level portion with interface height *H'* by 30 minutes or less (i.e. the "elbow" occurs before 30 minutes), then Eq. A3 can be simplified using the relationship between *H'* and H_0 from Eq. A2, and the SVI is given by:

$$SVI = \frac{1000}{X_M} \quad (\text{mL/g}) \qquad \text{(A4)}$$

CHAPTER FIVE

ROLE OF MEASUREMENT PARAMETERS IN SVI-TYPE TESTS AND A PROPOSAL FOR ESTIMATING ZONE SETTLING PARAMETERS

This chapter contains the complete text of a paper submitted to *Water Research* (September, 1999). At this time no copyright has been assigned.

ROLE OF MEASUREMENT PARAMETERS IN SVI-TYPE TESTS AND A PROPOSAL FOR ESTIMATING ZONE SETTLING PARAMETERS

Christopher M. Bye and Peter L. Dold

Dept. of Civil Engineering, McMaster University,

1280 Main Street West, Hamilton, Ontario L8S 4L7, Canada.

ABSTRACT

SVI-type activated sludge settleability measures are applied frequently in the design and control of secondary settling tanks. Considerable confusion exists as to which of the common settleability measures (SVI, DSVI, SSVI, $SSVI_{3.5}$) should be used. Experimental data are presented to demonstrate that differences in column height and sludge concentration can lead to large differences in calculated SVI even when the zone settling characteristics do not change. A model is used to further highlight these potential problems and evaluate the effects of sludge characteristics and test parameters on SVI-type indices. Sludge settleability and compactability, settling column height, and sludge concentration in the test have an interactive effect on the measured SVI. The experimental data and the model explain many of the artifacts historically associated with the SVI and raise considerable doubt regarding the validity of correlations for zone settling parameters based on SVI-type measures. An alternative SVI-based method is proposed for determining zone settling parameters.

Key words: Activated sludge, settleability, flux theory, zone settling velocity, SVI, DSVI, SSVI.

INTRODUCTION

Sludge settling characteristics are very important in suspended growth activated sludge systems. Sludge Volume Index (SVI) measurements are applied widely to monitor sludge settleability. Experience has shown the measure to be a very useful tool in routine process control. A primary reason for the popularity of the SVI and other SVI-type measures is that the tests are rapid and easy to perform.

A number of variants of the SVI have been developed [Stirred Specific Volume Index (SSVI), Stirred Specific Volume Index @ 3.5 g/L ($SSVI_{3.5}$), and Diluted Sludge Volume Index (DSVI)] to address perceived deficiencies in the SVI measure. For example, the DSVI was proposed to address the dependence of SVI on solids concentration. Another example is the SSVI proposed by White (1976) which specifically requires stirring. At that time the SVI test methodology as per *Standard Methods* (pre-1980) did not specify a requirement for stirring. *Standard Methods* was modified in 1980 to include stirring in the procedure for the SVI test. That is, the post-1980 *Standard Methods* SVI and the White SSVI both require stirring. Nevertheless, in current practice the SVI often is performed without stirring, and there appears to be a widespread misconception that an unstirred SVI is the "Standard Method". This misunderstanding continues to be propagated by researchers; for example, the recent IAWQ (1997) authoritative report on secondary settling states specifically that the SVI is "unstirred".

In the methods for conducting the tests, information usually is given about the type of apparatus to be used. However, there is not consistency regarding the dimensions of the column. For example, White (1976) specified a minimum diameter of 100 mm, but was not specific about the column height, suggesting 500 mm. *Standard Methods* specifies that the SVI should be performed in a 1 litre cylinder (which typically has a diameter of 60 mm and height of 350 mm, approximately). [In contrast, *Standard Methods* specifies a column "at least 1 m high and 10 cm in diameter" for the zone settling rate test].

This paper demonstrates that solids concentration and column height are critical in the outcome of the SVI-type measures. The view of the authors is that these aspects have been overlooked in the interpretation of SVI results. Experimental data that highlight these effects are presented. Understanding and interpreting how and why the calculated SVI value depends on concentration and column height is facilitated by using a model for predicting the change in interface height with time observed in a settling test. The model and experimental data reveal interesting characteristics about the DSVI; namely, that DSVI is an indirect measure of sludge compactability rather than settling characteristics *per se*. All of these features identify the need to develop a standardised SVI testing protocol for monitoring sludge settleability.

Activated sludge used in the column settling tests was drawn from a municipal sewage treatment plant in Dundas, Ontario. Settling tests were performed in both tall (100 cm height) and short (50 cm height) columns with and without slow stirring. The 30 minute interface height was noted for calculating the SVI for each test. Also, each test was allowed to run until settlement essentially had ceased to obtain an estimate of the compactability of the sludge.

BACKGROUND

Essentially all settling tests subject a given mixed liquor sample to similar conditions. That is, the sample is placed in a vessel (usually a cylinder), mixed well, and then allowed to settle. The behaviour with time in a typical column settling test is illustrated in Figure 5.1. At the start there may be a short lag period where little settlement takes place; during this phase the mixed biosolids reflocculate and a sludge-water interface forms. The next phase is a linear zone (or hindered) settling portion in which the sludge-water interface settles at a constant velocity. This zone settling phase is followed by a curvilinear transition stage between zone settling and compression settling. Finally, there is a level portion where minimal further settling takes place because the sludge has compacted to the highest degree possible under gravity settling conditions.

The SVI was developed to yield a rapid assessment of sludge settleability. A sample is placed in a cylinder, mixed well, and allowed to settle for an arbitrary time of 30 minutes. The 30-minute settled height (H_{30}) is noted. Dividing this by the initial height (H_0) of the sludge in the column yields the settled volume fraction. Using this value and the initial solids concentration (X_0, measured in g/L), the SVI is calculated as follows:

$$SVI = \frac{H_{30}/H_0}{X_0} \cdot 1000 \qquad (mL/g) \tag{1}$$

Multiplying by 1,000 normalizes the result to a 1-litre cylinder basis.

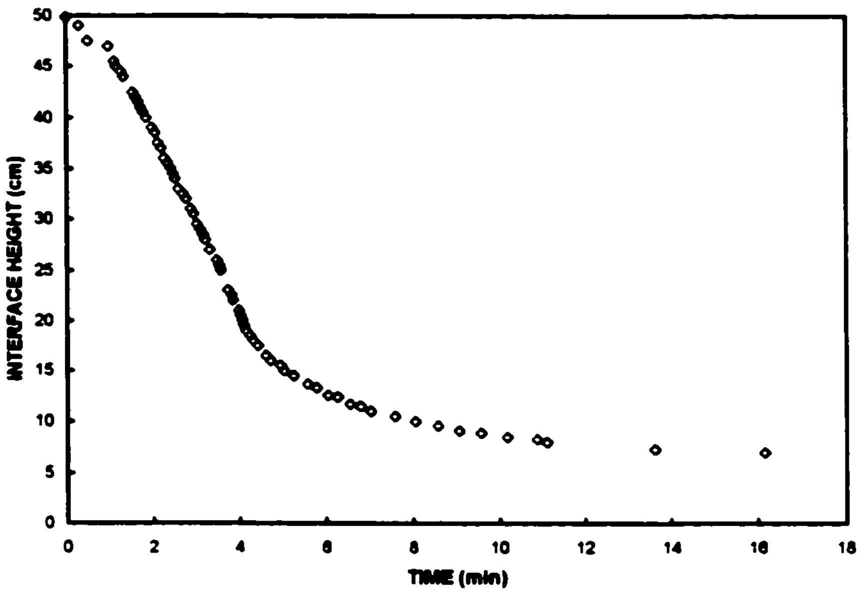

Figure 5.1: Typical settling profile.

A number of relationships which attempt to model the zone settling phase of a settling test have been proposed. Of these, the empirical Vesilind equation that describes how zone settling velocity (ZSV or V_S) changes with solids concentration (X) is most commonly used:

$$V_S = V_0 \, e^{-KX} \tag{2}$$

Quantifying the ZSV/X Vesilind function parameters (i.e. V_0 and K in Eq.2) requires considerable experimental effort. This has lead to the development of a number of correlations [Koopman & Cadee (1983); Pitman (1984); Daigger & Roper (1985); Ekama

& Marais (1986); Wahlberg & Keinath (1988); Daigger (1995); Ozinsky & Ekama (1995)] for the two ZSV model parameters based on SVI-type measures.

COLUMN HEIGHT

Much attention has been given to the fact that SVI varies with solids concentration. Surprisingly, little attention has been given to the effect of column height on SVI. In this section this effect is illustrated, and the underlying cause is explained and supported with experimental results.

The SVI test starts with a column filled to a height H_0 with a well-mixed sludge sample of concentration X_0. Equation 2 dictates that the solids-water interface that forms under these conditions moves down the column at a constant rate, V_S. Therefore, the interface height at time t is given by:

$$H(t) = H_0 - V_0\, e^{-KX_0} \cdot t \tag{3}$$

Figure 5.2 shows a representation of Eq. 3 as well as the points used in SVI calculation.

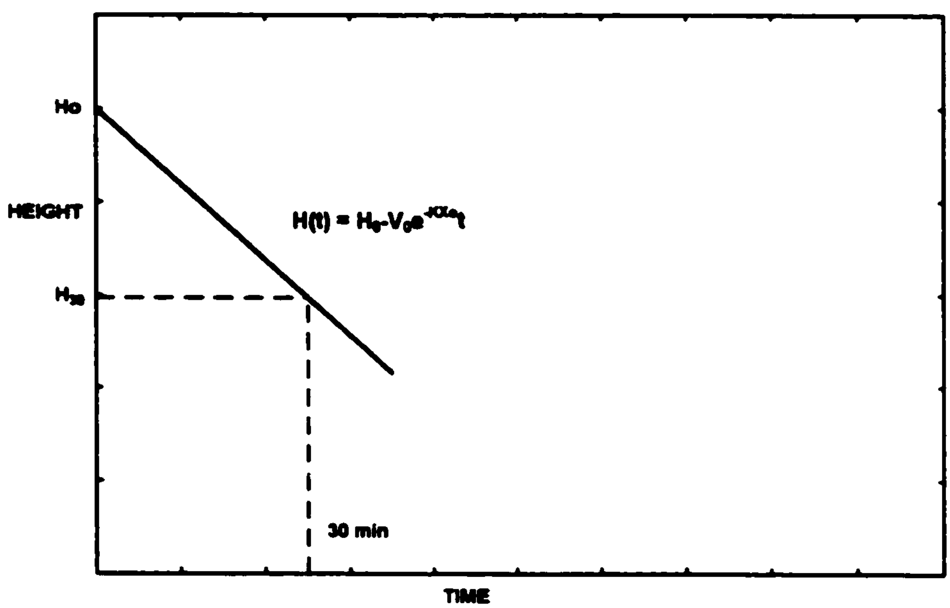

Figure 5.2: Points used in SVI calculation.

If Eq. 3 is substituted into Eq. 1, it is evident that SVI is given by (with t = 30 minutes):

$$SVI = \frac{H_0 - \{V_0 e^{-KX_0} \cdot t\}}{X_0 H_0} \cdot 1000 \qquad (4)$$

Equation 4 shows that SVI is dependant on column height, H_0. As an example, consider two parallel SVI tests conducted on a sludge sample in columns with heights of 100 and 200 centimetres, respectively. If the sludge has Vesilind settling characteristics V_0 and K of 7.2 m/h and 0.40 m^3/kg, respectively, and the tests are conducted at an initial solids concentration of 5 g/L, the SVI values given by Eq. 4 are:

$$SVI_{100} = 102 \text{ mL/g}$$

$$SVI_{200} = 151 \text{ mL/g}$$

In this case tests conducted on the *same* sludge sample with the *same* settling characteristics exhibit a 50% difference in SVI for the different column heights. Actually there are three possible scenarios for comparing SVIs conducted on a sludge sample in columns with different heights. These cases are shown in Figure 5.3.

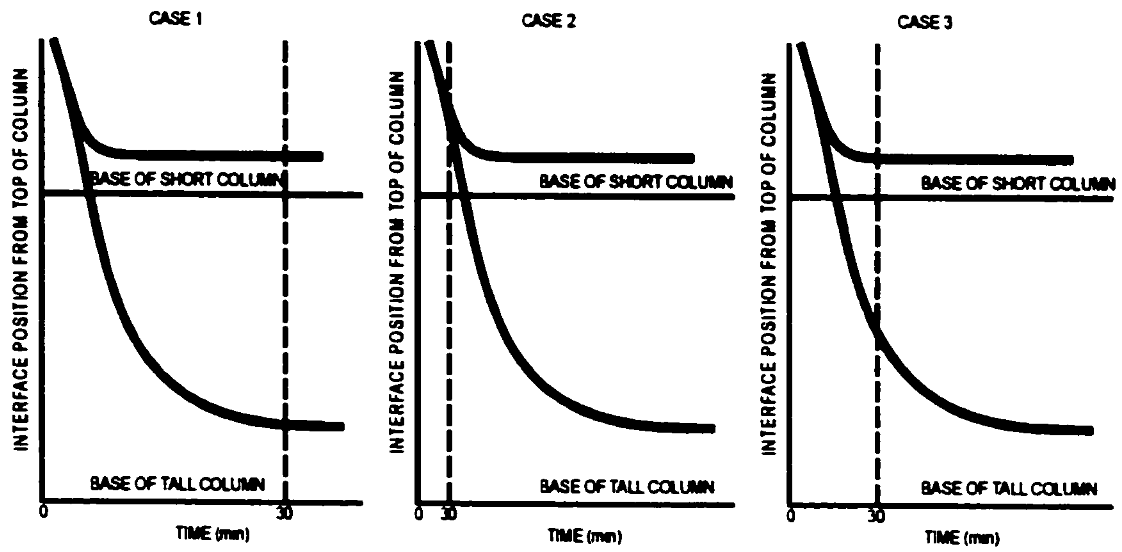

Figure 5.3: Possible scenarios showing effect of column height on SVI.

In Case 1, the sludge has settled rapidly and the compaction phase has been reached in both the tall and short column before 30 minutes have elapsed. In this case the SVI values for the different column heights will be the same [this is explained later (also see

Bye & Dold, 1998)]. For Case 2, the sludge has settled slowly and both samples are still exhibiting zone settling behaviour at 30 minutes. The previous example calculation which showed that the SVIs for the different column heights may be substantially different was an illustration of this situation. Case 3 shows the intermediate situation where the sludge has settled rapidly enough to reach the compaction phase in the short column, but not rapidly enough to do so in the tall column. In this case, it will be shown that the difference in SVI values may be even more substantial than that seen for Case 2 scenarios. Figure 5.4 illustrates the Case 3 scenario with experimental data.

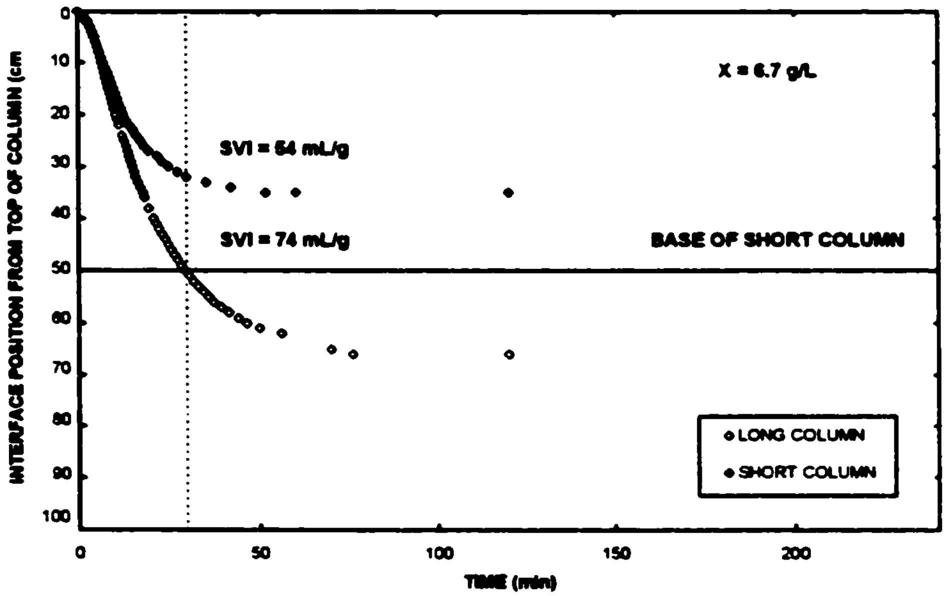

Figure 5.4: Experimental data illustrating Case 3 scenario.

SOLIDS CONCENTRATION

Much attention has been given to the dependence of SVI on solids concentration, as first noted by Dick and Vesilind (1969). A typical SVI-solids concentration curve illustrating this behaviour is shown in Figure 5.5. The experimental data show that the solids concentration dependence of the SVI can be quite dramatic. The measured SVI varied from about 90 mL/g to 150 mL/g over a concentration range of 4.5 to 6 g/L. Three characteristic regions in the SVI-solids concentration curve are evident. At low solids concentrations the SVI tends to be constant with increasing concentration up to a certain value (Region I). At this point, there is a rapid increase in SVI with a further increase in concentration (Region II). The increase in SVI continues until a peak value is reached, after which the SVI begins to *decrease* with increasing solids concentration (Region III).

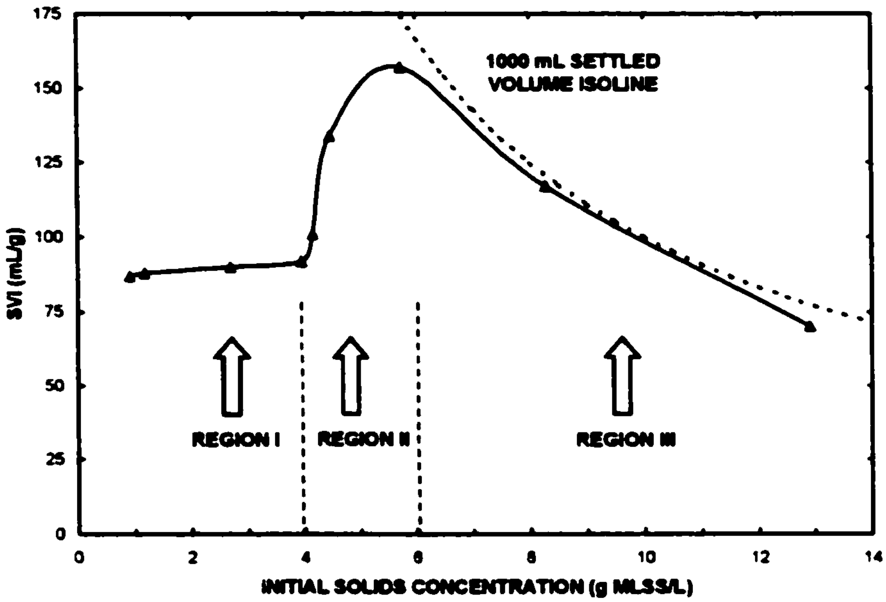

Figure 5.5: Typical SVI-solids concentration relationship (after Dick and Vesilind, 1969).

Researchers have explained the observed variation of SVI with initial solids concentration only in part. For example, Ekama and Marais (1984) explained the apparent *decrease* in SVI with increasing concentration (Region III) by introducing the isoline shown in Figure 5.5 corresponding to the case where no settling has taken place at a particular concentration. That is, the decrease in SVI does not occur because of an "improvement" in settleability; rather, the decrease is merely an artifact of the SVI calculation method.

No definitive explanation has been provided for the other two regions in the SVI-solids concentration curve. However, the middle region (Region II) where SVI undergoes a rapid change for a relatively small increase in solids concentration also can be anticipated. Again, this is an artifact of the SVI calculation method rather than a "deterioration" in settleability. Inspection of Eq. 4 shows that SVI is a non-linear function of solids concentration due to the exponential manner in which settling velocity decreases with increasing solids concentration. Figure 5.6 shows a plot of Eq. 4 illustrating the expected variation in SVI in Regions I and II for the case of a sludge with Vesilind settling characteristics V_0 and K of 7.2 m/h and 0.40 m^3/kg, respectively. The predicted variation in SVI is very similar to that shown for the experimental data in Figure 5.5.

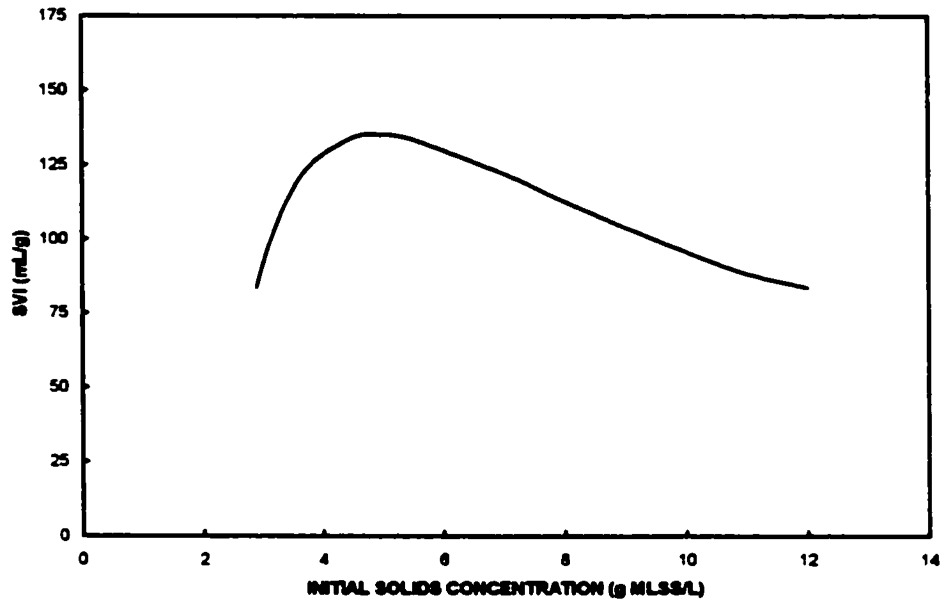

Figure 5.6: Plot of Equation 4 showing that a variation in SVI with solids concentration is anticipated.

The extent of the variation of S'/I with concentration in Regions II and III essentially depends on both the settling column height and the sludge settleability (i.e. Vesilind settling characteristics V_0 and K). This will be illustrated later. The fact that SVI changes with concentration in Regions II and III has been used as the principal basis for criticizing SVI as a measure of sludge settleability, and has motivated the adoption of DSVI as a preferred measure. That is, SVI measured at low initial solids concentration in Region I where SVI appears independent of concentration.

DSVI and SOLIDS COMPACTABILITY

In the DSVI test, the procedure for the SVI test is applied to serial dilutions of the mixed liquor sample until the 30-minute settled volume is less than 250 mL. In effect this forces the SVI measurement regime "to the left" in Figure 5.5 (Region I). Figure 5.7 shows an isoline representing the case in which the 30-minute settled volume (SV_{30}) is 250 mL in a 1000 mL test volume. This illustrates the basis for the DSVI; namely, that if a sludge sample settles rapidly enough to reach a height less than approximately ¼ of the initial height, SVI will be approximately constant for other samples of lower initial solids concentration.

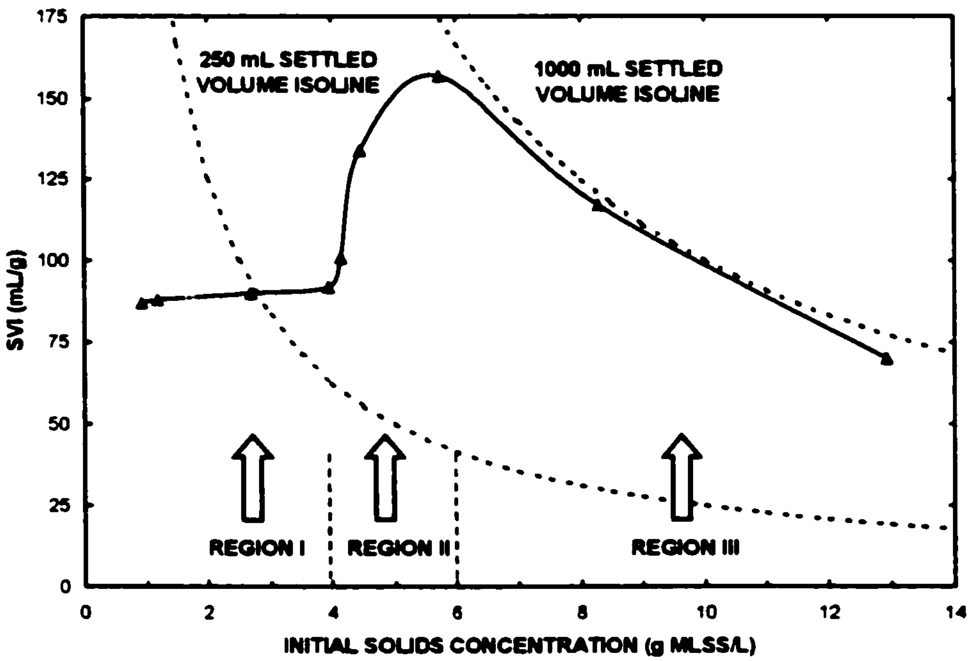

Figure 5.7: SVI-solids concentration data showing 250 mL settled volume isoline.

The fact that SVI (actually DSVI) does not change appreciably with concentration at the diluted initial concentrations in Region I can also be anticipated by considering what happens under these measurement conditions. At the lower test concentrations the zone settling velocity will be increased. The characteristic of the DSVI test is that the transition from zone settling behaviour to compression and compaction has occurred before the interface height is noted at 30 minutes. That is, the DSVI test conditions correspond to Case 1 in Figure 5.3, where zone settling essentially is complete. This is shown in an idealized fashion in Figure 5.8. For this situation the height of the 30-minute solids-liquid interface used in the calculation of SVI (i.e. DSVI) essentially is determined by the compactability of the sludge. If X_M represents the concentration of the compacted sludge, the height of the sludge in the column after settling is complete, H', is given by a simple mass balance:

$$X_M H' = X_0 H_0$$

$$H' = \frac{X_0 H_0}{X_M} \qquad (5)$$

Substituting in Eq. 3 yields:

$$\text{DSVI} = \frac{1000}{X_M} \qquad (\text{mL/g}) \qquad (6)$$

Equation 6 shows that, for any test where settling is complete before the 30 minute cut-off, the SVI (i.e. DSVI) is only a function of the sludge compactability, X_M. That is, the SVI is "constant", irrespective of initial sludge concentration. This interpretation provides an explanation for the behaviour in Region I of Figure 5.3.

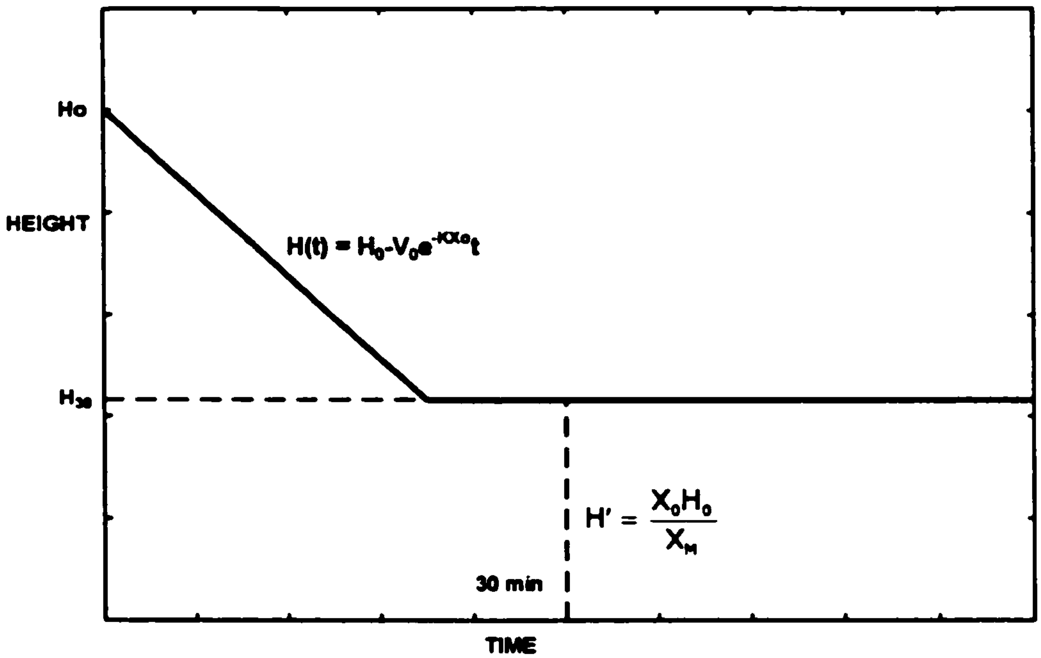

Figure 5.8: Idealized settling profile.

The explanation of DSVI above implicitly assumes that X_M is a "constant" characteristic for a particular sludge (at least for the conditions of the SVI test). This can be supported by experimental data. To illustrate this point, a series of settling tests were conducted in a 500 mm column on samples of the same sludge spanning a range of concentrations from 560 to 10,500 mg/L. Rather than noting the 30-minute interface height, each test was allowed to continue for an extended period of several hours, and the height was noted after settlement was complete (i.e. the final settled height). Figure 5.9 shows a plot of the final settled height (as a fraction of the column height) *versus* the initial sludge concentration in each test. The fact that the data essentially are linear confirms that the final compacted sludge concentration in each test is near uniform (i.e. X_M given by the reciprocal of the slope in Figure 5.9). That is, for tests at higher initial concentrations, and thus higher final heights of compacted sludge, the mass of sludge in the upper layers is not further compacting sludge in the lower layers.

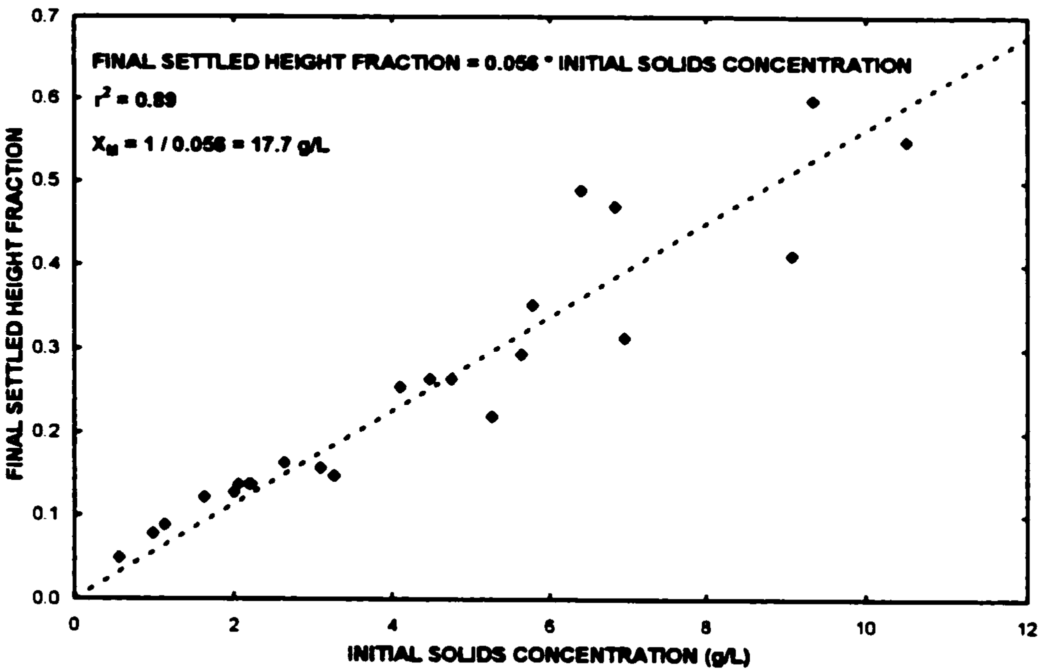

Figure 5.9: Relationship between solids concentration and final settled height.

In the DSVI regime (where settlement is complete), the DSVI value essentially is a measure of the sludge compactability, X_M, rather than settleability *per se*. For example, sludges with very different settling properties, but with the same compactability X_M, will have the same DSVI. This situation is depicted in Figure 5.10. Irrespective of whether the settling rate is rapid or slow, as long as settlement essentially is complete before 30 minutes, the SVI value will be the same for each sludge. Nevertheless, there probably is a link between DSVI and settleability. For example, it is likely that a poor settling sludge (e.g. a filamentous bulking sludge) will not compact well (i.e. a small X_M) and therefore will exhibit a high DSVI according to Eq. 6.

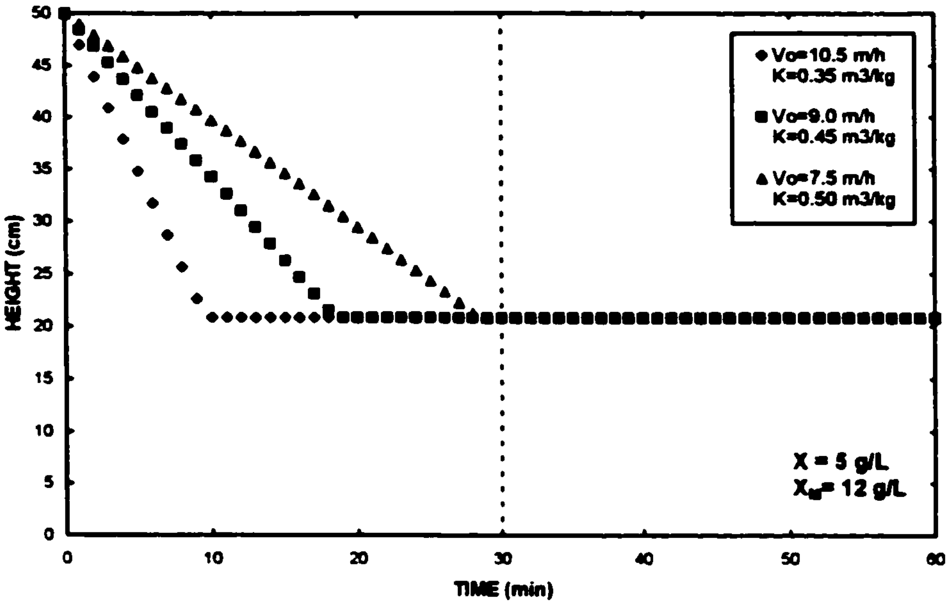

Figure 5.10: Sludge with different zone settling characteristics may still have the same DSVI.

SUMMARIZING THE IMPACT OF COLUMN HEIGHT, CONCENTRATION AND SLUDGE COMPACTABILITY

The foregoing discussion addressed and explained the impact of column height, initial MLSS concentration, and sludge compactability on SVI-type tests. In this section the interactive effect of the three parameters is demonstrated in a generalized form. The basis for conducting this analysis is through simulating the idealized behaviour observed in a settling test, as depicted in Figure 5.8 [see also Bye and Dold (1998)]. To demonstrate the effect of, say, initial sludge concentration, the settling test can be simulated for a range of initial concentrations [while holding H_0, X_M, V_0 and K constant], and the SVI values can be calculated from the 30-minute solid-liquid interface height. This is equivalent to applying Eq. 6 (for Region I) and Eq. 4 (for Regions II and III). An example of an SVI - Solids Concentration profile generated by this approach for a given sludge sample over a range of concentrations is shown in Figure 5.11. This generates the same trend in SVI with increasing sludge concentration as shown for experimental data in Figure 5.5; namely:

- At low concentrations ($X_0 < 3$ g/L in this case) the SVI is constant for increasing concentration (approximately 45 mL/g).
- As test concentration increases there is a rapid increase in SVI to a maximum (approximately 100 mL/g at $X_0 = 6$ g/L in this case).
- For further increases in concentration the SVI decreases, following a curve which represents little or no settlement in the test.

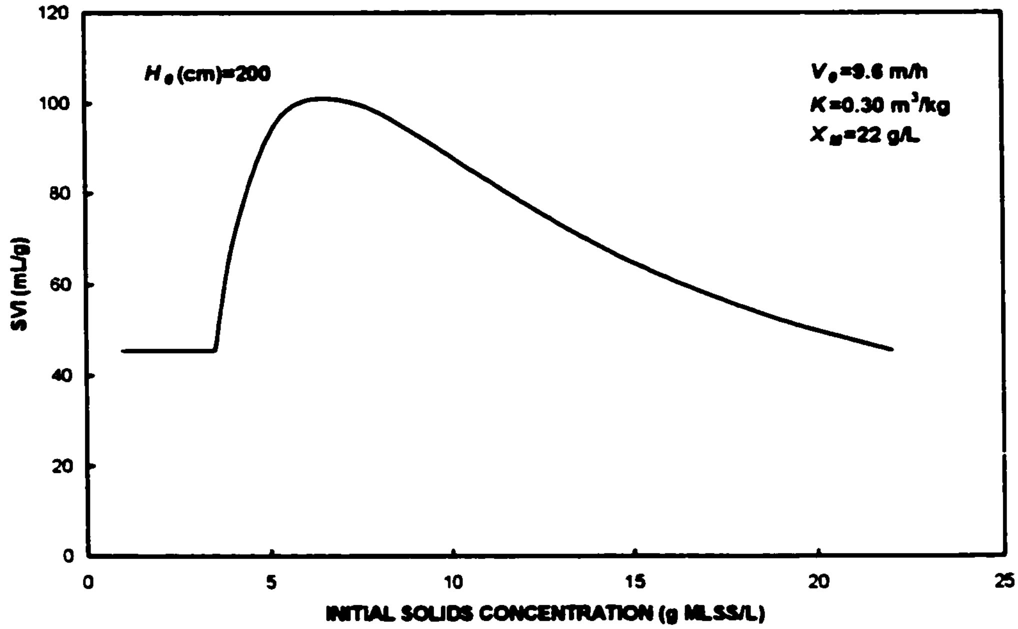

Figure 5.11: Model-generated SVI-concentration curve.

Effect of Column Height:

SVI-X_0 curves for tests in columns with heights of 50, 100, 150 and 200 cm were generated for a sludge sample with fixed settling characteristics; the results appear in Figure 5.12. Each case shows the SVI trend with increasing solids concentration evident in Figure 5.11. It is also evident that:

- The range of possible SVI values from the minimum attainable SVI (i.e. the DSVI) to the peak SVI increases with increasing column height. For the 50 cm column SVI essentially is independent of solids concentration because the sludge interface height in the short column has reached H' at or before 30 minutes for all but the highest concentrations. For the 200 cm column the SVI values range from 83 to 160 mL/g.

- In each case, as concentration increases, at some point there is a transition from the constant SVI (i.e. the DSVI) to an increasing SVI. The transition occurs at lower concentrations as column height increases. This is a consequence of the difference in (H_0 - H'). With a shorter column, the distance that must be covered to reach H' is decreased, making it easier for the sludge interface to reach H' at or before 30 minutes. Thus a greater number of sludge concentrations are able to reach H' at or before 30 minutes, making the SVI less dependent on solids concentration.

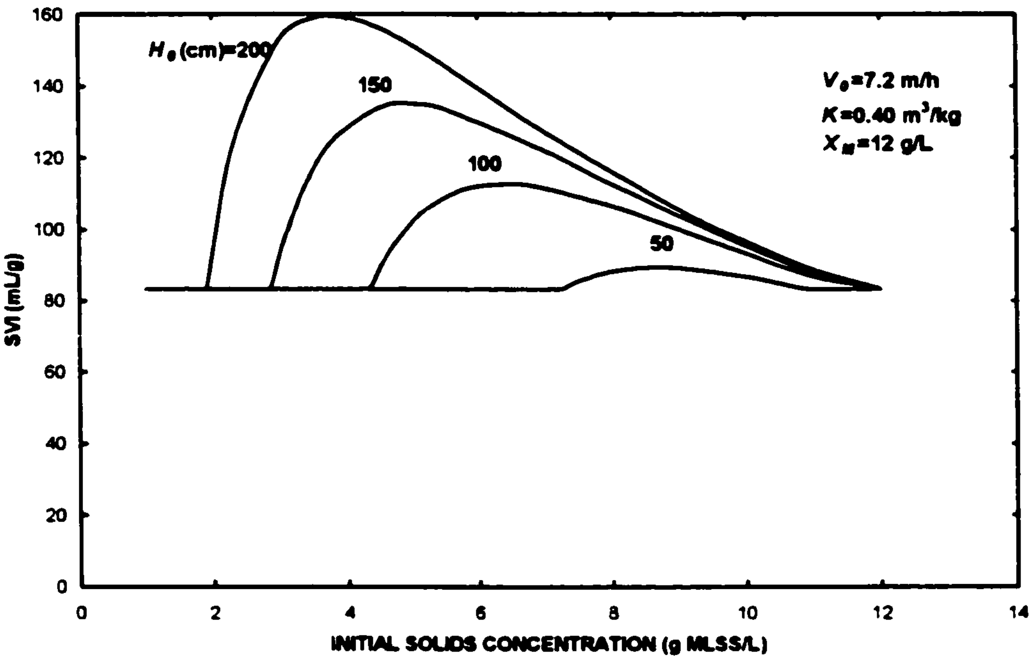

Figure 5.12: SVI - solids concentration curve for different settling column heights with poor settling sludge.

Effect of Zone Settling Parameters:

The results in Figure 5.8 were generated for a "poor" settling sludge sample with a low V_0 of 7.2 m/h and a high K of 0.40 m^3/kg. To illustrate the effect that the zone settling parameters have on the SVI - Solids Concentration relationship, the SVI-X_0 curves in Figure 5.12 ("poor" settling characteristics) were regenerated for the same set of parameters, but for changed V_0 and K (a higher V_0 of 9.6 m/h and a lower K of 0.30 m^3/kg). The results for this sample with "good" settling characteristics are shown in Figure 5.13. From a comparison of Figures 5.12 and 5.13 it is evident that the effect of column height is less pronounced when the sludge have "good" settling characteristics. In Figure 5.13 SVI is independent of solids concentration for both the 50 and 100 cm columns. This is because the sludge interface height has reached H' at or before 30 minutes for all concentrations with the rapidly settling sample. Even for the 150 cm column, SVI dependence on solids concentration is minimal. For the 200 cm column, the SVI values range from 83 mL/g to just over 100 mL/g, which is a much smaller range than for the case of "poor" settling solids.

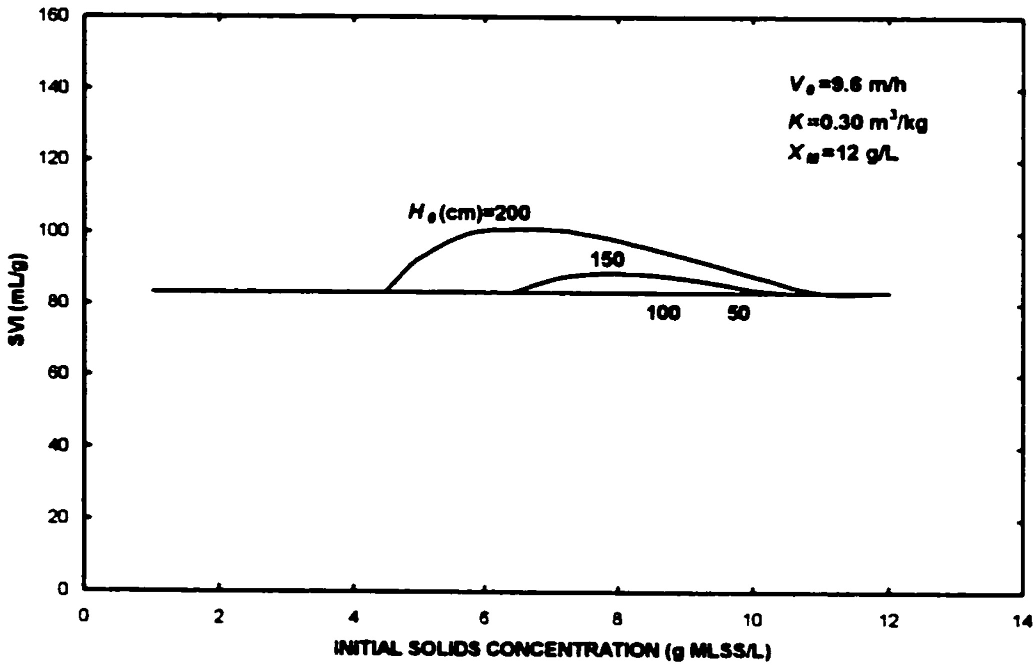

Figure 5.13: SVI - solids concentration curve for different settling column heights with good settling sludge.

CONCLUSIONS

SVI-type measures no doubt will, and should, continue to be used in plant operations as a useful indicator of sludge settleability and/or changes in settleability. This paper does not aim to question the utility of this approach. Rather, the objective has been to illustrate that many of the artifacts associated with the SVI cited by researchers over the years can be explained logically. As an example, if two sludges from different plants were reported to have SVIs of 60 and 150 mL/g, respectively, it likely would be assumed that the settleability of the former was significantly better than the latter, and that the latter in fact was a bulking sludge. However, the settleabilities (in terms of zone settling rate) quite possibly could be identical, and the difference could be due to conducting the tests in columns with different column heights or at different test concentrations.

In assessing information on SVI-type measures, two important factors to recognize are that:

- Depending on column height and sludge settleability, the SVI for a sample with given settling characteristics may well change appreciably with initial concentration, even for small changes in concentration. This becomes more evident as the height of the settling column increase.
- The DSVI test "forces" the SVI test conditions into the region where SVI is independent of solids concentration. Intuitively it may seem that this is a suitable measuring state. However, in this region the observed SVI is not determined directly by the settleability of the test sample. Rather, the DSVI provides a measure of sludge compactability.

This paper on SVI and DSVI as sludge settleability measures would be incomplete without a comment on correlations for zone settling parameters (V_0 and K) based on SVI or DSVI. As a general statement, mathematically it would appear somewhat dubious that two parameters in a model such as Eq. 2 that quantifies how solids concentration (X) influences ZSV can be estimated based on a single SVI value from a test conducted at a single X value. Irrespective, the results presented in the paper question the validity of the correlations [see also Dold and Bye (1999)]. With regard to DSVI, from Figure 5.10 for example, it is evident that three samples with very different zone settling parameters (*V_0* and *K*) can have the same DSVI. However, a correlation based on DSVI will predict the same *V_0* and *K*. With regard to SVI, the results show that a sample with given zone settling parameters (*V_0* and *K*) can exhibit a wide range of SVI values even for small variations in concentration in the test. However, a correlation based on SVI will predict widely different pairs of *V_0* and *K* values. [At the risk of labouring the point, a further complication regarding the correlations based on SVI is that the correlations were developed using SVI values from settling columns of widely differing heights – and these may differ substantially].

The attraction of applying the correlations is that it obviates the need to conduct time-consuming settling tests. However, if the results are questionable as contended here, perhaps the following approach would provide a compromise for determining the Vesilind zone settling parameters (*V_0* and *K*):

1. Conduct a number of stirred SVI tests in a settling column over a range of sludge concentrations (from approximately 1 to 10 or 12 g/L, depending on the settling characteristics), including tests in the DSVI range. Six tests may be sufficient, but the level of confidence in the estimates for *V_0* and *K* should improve if more tests are conducted.

2. Calculate the SVI value for each test using Eq. 1 based on the 30-minute interface height *in the settling column*, not in a separate 1-litre SVI test.

3. Plot the measured SVI values *versus* the initial sludge concentration in each test; see Figure 5.14. The data must exhibit a "hump" in the intermediate concentration range. This may necessitate using a tall column, depending on the settling characteristics (see Figures 5.12 and 5.13). Typically a 2 metre high column (with diameter of 150 mm) should be appropriate. However, the column should be short enough to include SVIs in the DSVI range.

4. Apply Eq. 6 in the low concentration range, adjusting the sludge compactability, X_M, to fit the data. [This step is not essential for determining V_0 and K].

5. Apply Eq. 4 in the higher concentration range, adjusting the Vesilind zone settling parameters (V_0 and K) to fit the data. [Note that Eq. 4 is only valid for sludge concentrations that yield SVI values greater than $1000/X_M$, the DSVI]. An example is shown in Figure 5.14.

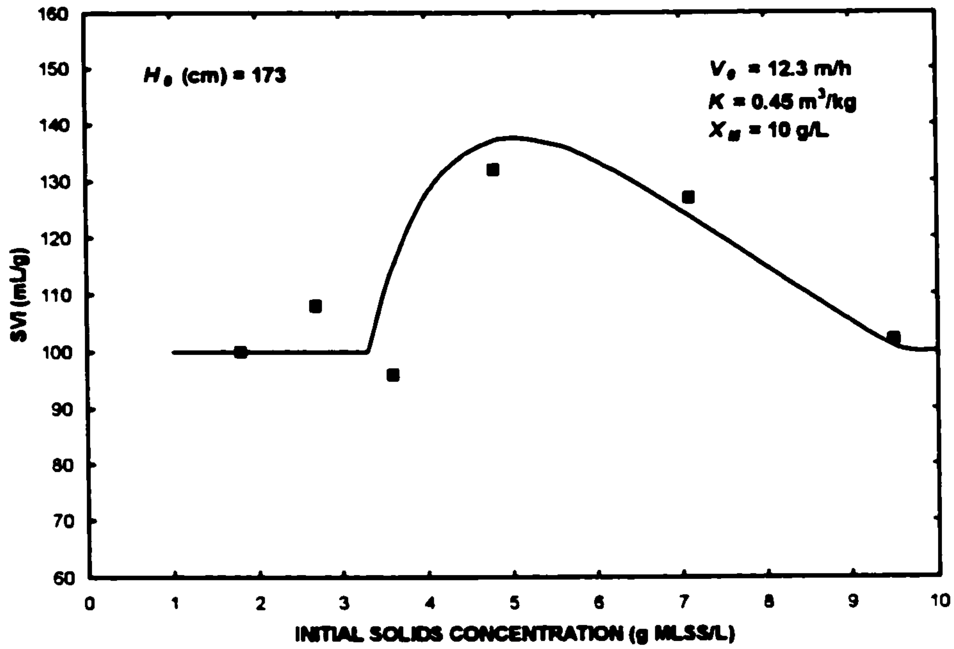

Figure 5.14: Simulated SVI *versus* Solids Concentration profile (solid line) compared to measured data.

The proposed method for estimating the Vesilind zone settling parameters (V_0 and K) is based on a number of SVI measurements over a range of concentrations (including the DSVI region), thereby allowing the impact of sludge concentration to become evident. For some time there has been strong support in favour of DSVI rather than SVI. For example, Lee *et al.* (1983) stated that "it is appropriate now that the standard SVI, after 45 years of use, be supplanted by an index more directly applicable to activated sludge process design and operation. Universal adoption of the diluted SVI as this index would represent a significant and timely advancement in the field of water pollution control".

The IAWQ (1997) task group on secondary settling added to this suggestion by stating that "the continued use of the SVI after a further 13 years of use cannot be cogently argued". These comments may be entirely appropriate in terms of (1) the issue of stirred *versus* unstirred SVI [we support only the stirred test], and (2) DSVI being preferable to SVI as a single parameter for monitoring plant performance in the field [because DSVI reflects sludge compactability which, in turn, probably reflects sludge settleability]. However, the essence of the proposed method is that DSVI only provides information in a very restricted concentration range (where in fact the data does not reflect the impact of concentration on settling rate). To derive information on the effect of sludge concentration on settleability, SVI measurements over a range of concentrations are required. Therefore, in terms of providing information on zone settling characteristics, SVI data are essential, and the *stirred* SVI test (i.e. the *Standard Method*) should not be rejected out of hand.

The views expressed in this paper may cause some controversy. Irrespective, it should be very evident that there is a need in the wastewater treatment field for standardisation of the apparatus used for conducting SVI-type tests in terms of diameter and height. In addition, the confusion over stirred *versus* unstirred SVIs should be clarified. Even though *Standard Methods* specifies stirring in the 1-litre SVI test, it is likely that many practitioners will continue to conduct tests without stirring. It is suggested that the latter should be identified as the uSVI test, and that the *Standard Methods* SVI test should be denoted as the sSVI.

ACKNOWLEDGEMENT
This study formed part of the activities of the Natural Sciences and Engineering Research Council (NSERC) / Wastewater Technology Centre Industrial Chair in Environmental Systems Engineering. The Support of the Chair sponsors is acknowledged.

REFERENCES

Bye C.M. and Dold P.L. (1998) Sludge volume index settleability measures: effects of solids characteristics and test parameters. *Water Environment Research* **70**, 87-93.

Bye C.M. and Dold P.L. (1999). Evaluation of correlations for zone settling velocity parameters based on SVI-type measures and consequences in settling tank design. *Water Environment Research* **71**, 1333-1344.

Daigger G.T. and Roper R.E. (1985) The relationship between SVI and activated sludge settling characteristics. *Journal WPCF* **57**, 859-866.

Daigger G.T. (1995) Development of refined clarifier operating diagrams using an updated settling characteristics database. *Water Environment Research* **67**, 95-100.

Dick R.I. and Vesilind P.A. (1969) The sludge volume index - what is it? *Journal WPCF* **41**, 1285-1291.

Ekama G.A. and Marais G.v.R. (1984) Two improved activated sludge settleability parameters. *IMIESA* **9**, 20-27.

Ekama G.A. and Marais G.v.R. (1986) Sludge settleability and secondary settling tank design procedures. *Wat. Pollut. Control* **85**, 101-113.

IAWQ - Ekama G.A., Barnard J.L., Gunthert F.W., Krebs P., McCorquodale J.A., Parker D.S. and Wahlberg E.J. (1997) Secondary settling tanks: theory, modelling, design and operation. Scientific and Technical Report No. 6, International Association on Water Quality, London, England.

Koopman B. and Cadee K. (1983) Prediction of thickening capacity using diluted sludge volume index. *Water Research* **17**, 1427-1431.

Lee S.-E., Koopman B., Bode H. and Jenkins D. (1983) Evaluation of alternative sludge settleability indices. *Water Research* **17**, 1421-1426.

Ozinsky A.E. and Ekama G.A. (1995) Secondary settling tank modelling and design Part 2: Linking sludge settleability measures. *Water SA* **21**, 333-350.

Pitman A.R. (1984) Settling of nutrient removal activated sludges. *Wat. Sci. Technol.* **17** (Amsterdam), 493-504.

Standard Methods for the Examination of Water and Wastewater, 15th ed. (1980) American Public Health Association, Washington, D.C., 20005, USA.

Standard Methods for the Examination of Water and Wastewater, 20th ed. (1998) American Public Health Association, Washington, D.C., 20005, USA.

Wahlberg E.J. and Keinath T.M. (1988) Development of settling flux curves using SVI. *Journal WPCF* **60**, 2095-2100.

White, M.J.D. (1976) Design and control of secondary settlement tanks. *Wat. Pollut.Control* **75**, 459-467.

CHAPTER SIX

STABILITY PROBLEMS WITH ONE-DIMENSIONAL LAYERED SECONDARY SETTLING TANK MODELS

This chapter contains the complete text of a paper submitted to *Water Research* (September, 1999). At this time no copyright has been assigned.

STABILITY PROBLEMS WITH ONE-DIMENSIONAL LAYERED SECONDARY SETTLING TANK MODELS

Christopher M. Bye and Peter L. Dold

Dept. of Civil Engineering, McMaster University,
1280 Main Street West, Hamilton, Ontario L8S 4L7, Canada.

ABSTRACT

One-dimensional layered models appear to offer a compromise between the simplicity of manual flux analysis and the complexity of two and three-dimensional hydrodynamic models. A robust, stable one-dimensional layered model especially is useful when incorporated into a process simulator which captures the behaviour of the bioreactor-settler interaction. From the beginning, attempts to model the secondary setting tank process have been fraught with numerical stability and solution problems. This paper examines the approach used for two cases: (1) a steady-state continuous flow settler; and (2) an unsteady-state batch settler. Solution and stability problems are highlighted, and explanations for these are given.

KEYWORDS

Activated sludge, settleability, secondary settling tanks, one-dimensional modelling.

INTRODUCTION

Process simulators, which couple the bioreactor and secondary settling tank (and other treatment plant units), are being applied widely as tools in the design and optimization of activated sludge wastewater treatment plants. These simulators attempt to provide a realistic representation of treatment plant behaviour; for example, the shift in sludge inventory from the bioreactor to the settler during storm events, and the impact on effluent quality. There can be significant interactions between the bioreactor and the secondary settling tank (SST). The two units are interactive because of the feedback from the SST underflow recycle to the bioreactor, and the change in solids loading to the SST with changes in influent flow rate.

Modelling of the SST can be extremely complex to account for factors such as tank geometry, flow patterns, baffle arrangements, surface wind shear, etc. Several two- and three-dimensional (2-D and 3-D) hydrodynamic models have been developed to address these issues, and have proven very useful in detailed SST analysis. However, such models are highly computational-intensive, and for this reason do not lend themselves to incorporation in PC-based treatment plant simulators. To avoid computation time limitations, the simplest approach in simulators has been to model the SST as an idealized two-cell unit. A compromise between this over-simplification and the complex 2-D and 3-D approach is to apply a one-dimensional (1-D) model. In terms of overall treatment plant simulation, 1-D models based on flux theory are adequate for many purposes because they can account reasonably for effects such as shifting sludge inventory. A further advantage of the 1-D models is that it is possible to include modelling of biological reactions within the settler without incurring excessive computational overhead.

In the one-dimensional approach, solids and liquid movement in the vertical direction are assumed to be dominant and horizontal movement is ignored. The settling tank is divided into a number of layers in the vertical direction and a numerical technique is used to solve the mass balance equations in the vertical direction. The solution to the mass balance equations provides the solids concentration profile in the settling tank, and the solids concentration in the effluent and underflow.

One problem encountered with these 1-D models is numerical instability and solution problems, particularly for steady state loading situations. The purpose of this paper is to investigate and demonstrate some of the instability problems associated with the traditional mass balance-based layered 1-D approach. This will be accomplished by examining the steady state case for a continuous flow SST situation and the unsteady state case of a batch settling test.

OBJECTIVE AND METHODS

Two techniques were employed to demonstrate the numerical instability and solution problems that may be observed in some cases when 1-D layered models are used to simulate settler behaviour. For the case of a continuous flow settler under steady state conditions, mass balance equations were written for the various settler regions (above the feed layer, the feed layer, and below the feed layer). These equations were input into a spreadsheet, and the solution behaviour of a layer was examined for varying overflow rates, underflow rates, and sludge settling characteristics. The mass balance equation was plotted to aid in the illustration of the solution problems that can be encountered for the steady state case. For the unsteady state case of a batch settling test, the mass balance equations were written and input into computer code so that the time-dependant behaviour of the batch settling test could be simulated. This behaviour was evaluated for various initial concentrations and sludge settling characteristics.

STEADY STATE CASE FOR A CONTINUOUS FLOW SETTLER

When considering a one-dimensional model of a secondary settling tank, one must consider the behaviour in three separate zones:

1. The zone above the feed layer.

2. The feed layer.

3. The zone below the feed layer.

This is necessary because the mass balance equations that describe a given layer change from zone to zone. Above the feed layer, the bulk fluid movement (i.e. surface overflow rate) is upwards, therefore any solids transport associated with the bulk fluid movement is upwards as well. Below the feed layer, the bulk fluid movement (i.e. underflow rate) is downwards, so solids transport associated with the bulk fluid movement also is downwards. At the feed layer, the solids mass loading of the feed must be considered, and there is both upwards and downwards bulk fluid movement. [It is assumed that the feed flow is the sum of the overflow and the underflow, and the "flow split" occurs in this layer]. Also, the top layer in the first zone (i.e. overflow) and the bottom layer in the third zone (i.e. underflow) require special consideration. The top layer in the first zone is unique as there is no solids flux into it. The bottom layer in the third zone is unique as there only is bulk flux out of it. Another requirement of one-dimensional secondary settling tank models is a quantitative relationship between solids concentration and settling velocity. In this study, the semi-logarithmic Vesilind relationship was used to quantify zone settling velocity, V_S:

$$V_s = V_0 e^{-KX} \qquad (m/d) \tag{1}$$

where X is solids concentration (gTSS/m^3), and V_0 (m/d) and K (m^3/kg) are experimentally determined parameters.

From the discussion above, the following steady state equations may be developed for a "single layer" in each zone:

$$V_{UP}(X_{i+1} - X_i) + V_0 e^{-KX_{i-1}} \cdot X_{i-1} - V_0 e^{-KX_i} \cdot X_i = 0 \quad \text{(above feed layer)} \tag{2}$$

$$V_{DN}(X_f - X_i) + V_{UP}(X_f - X_i) + V_0 e^{-KX_{i-1}} \cdot X_{i-1} - V_0 e^{-KX_i} \cdot X_i = 0 \quad \text{(feed layer)} \tag{3}$$

$$V_{DN}(X_{i-1} - X_i) + V_0 e^{-KX_{i-1}} \cdot X_{i-1} - V_0 e^{-KX_i} \cdot X_i = 0 \quad \text{(below feed layer)} \tag{4}$$

where V_{UP} is the surface overflow rate, V_{DN} is the underflow rate, X_f is the feed TSS concentration, X_{i-1} is the TSS concentration in the layer above the solution layer, X_{i+1} is the TSS concentration in the layer below the solution layer, and X_i is the TSS concentration in the solution layer.

For a steady state solution we wish to determine the solids concentration in each model layer. This is provided by the simultaneous solution of the mass balance equations for each layer. Because the equations are non-linear, an iterative solution procedure must be used, starting at an initial "guess" of the concentration profile.

To investigate the impact of operating parameters and sludge settleability parameters on the solution of these equations, the following procedure was used. A spreadsheet for each equation was set up in a manner that allowed any of the variables (e.g. overflow rate, underflow rate, feed TSS concentration, sludge settleability) to be changed. Then, for a specified X_{i-1} and X_{i+1}, the mass balance equation for the solution layer was plotted versus X_i. An example of such a plot is shown in Figure 6.1.

The solution to the steady state mass balance equation is given by the solids concentration for the layer that sets the mass balance equal to zero (i.e. the x-axis intercept in Figure 6.1). An advantage of this graphical approach is that it shows the *form* of the mass balance equation that is being solved, and indicates any potential solution difficulties. The behaviour of the mass balance equations for each zone will be discussed. Sludge settleability as characterized by the Vesilind parameters V_0 and K was classified as either "good" (V_0 = 240 m/d, K = 0.35 m^3/kg) or "poor" (V_0 = 168 m/d, K = 0.65 m^3/kg) (WRC, 1984). Overflow and underflow rates were varied between typical values of 16 - 32 m/d (Metcalf & Eddy, 1991). Feed concentration was varied between 3,000 - 6,000 gTSS/m^3 (Metcalf & Eddy, 1991). It should be noted here that results for all of the various combinations are not shown; however, results that illustrate points of interest are presented.

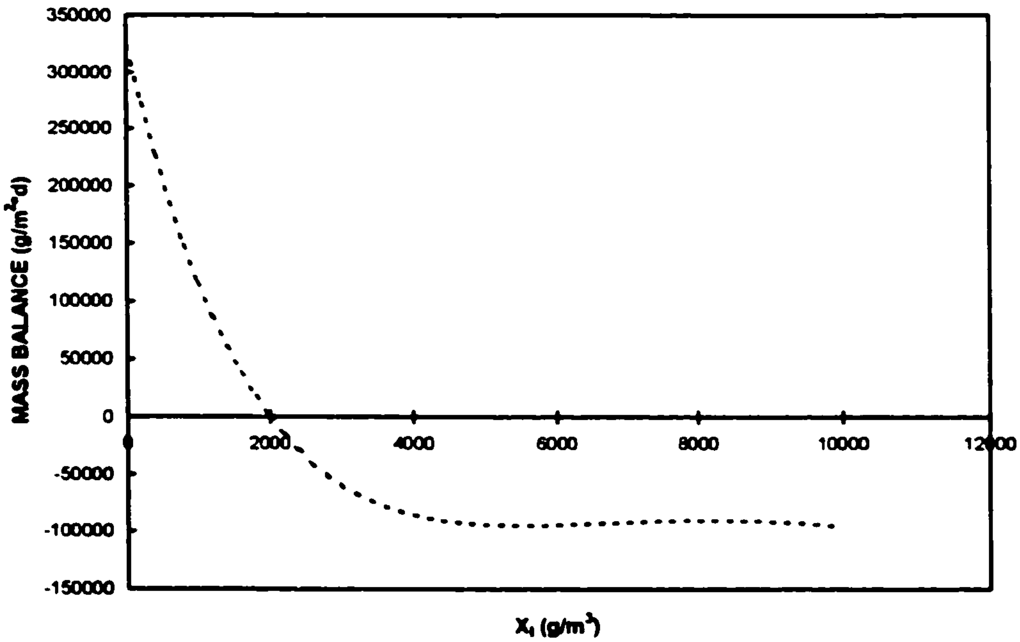

Figure 6.1: Mass balance equation for layer "*i*" versus concentration of layer "*i*".

Solution Behaviour Above Feed Layer

The first case investigated above the feed layer is where there are a small amount of solids (e.g. 10 mg/L) above the layer of interest and there are solids below the solution layer at a reasonably high concentration of X_{i+1} = 3,000 mg/L. This case simulates a critically loaded situation with a sludge blanket above the feed layer. The solution plot for "poor" settling sludge and an overflow rate of 20 m/d is shown in Figure 6.2. The solution plot shows that for the Case 1 scenario, the solution where the mass balance is satisfied (X_i = 416 mg/L) is well defined and sensible; that is, a small amount of solids are being carried upwards from the sludge blanket due to bulk liquid movement. Similar results were obtained for "good" settling sludge and other overflow rates in the specified range.

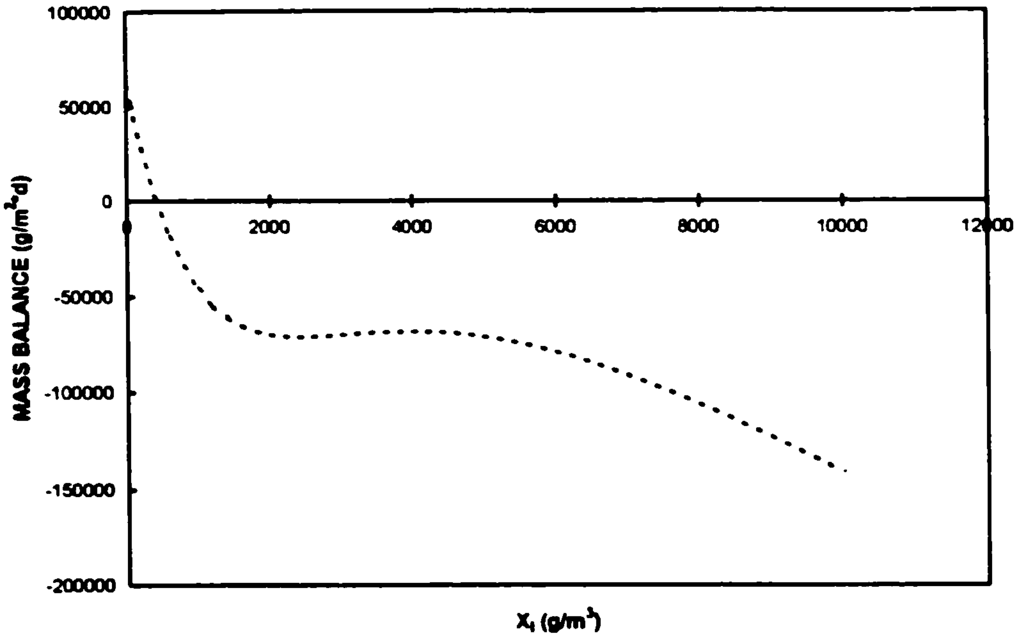

Figure 6.2: Solution plot for Case 1 above feed layer (X_{i-1} = 10 mg/L, X_{i+1} = 3,000 mg/L).

Case 2 is the situation where a concentration gradient has formed above the feed layer, with X_{i-1} = 2,000 mg/L and X_{i+1} = 3,000 mg/L. The solution plot for Case 2 with "good" settling solids and an overflow rate of 24 m/d is presented in Figure 6.3. This shows that the mass balance equation for a layer above the feed point can be very ill-conditioned for numerical solution. In this case there are three possible solutions to the mass balance equation for the conditions specified, only one of which is sensible (X_i = 2,500 mg/L). The mass balance equation for the conditions specified in Case 2 is sensitive to the initial guess used by the iterative solution technique if the desired solution is to be obtained. When the overflow rate is increased beyond 24 m/d, the problem of multiple solutions does not occur. With "poor" settling sludge, multiple solutions were not encountered; however, the solutions obtained over the entire range of overflow rates were non-sensible, i.e. the values of X_i which satisfy the mass balance equation are not between X_{i-1} and X_{i+1}, and therefore violate the concentration gradient.

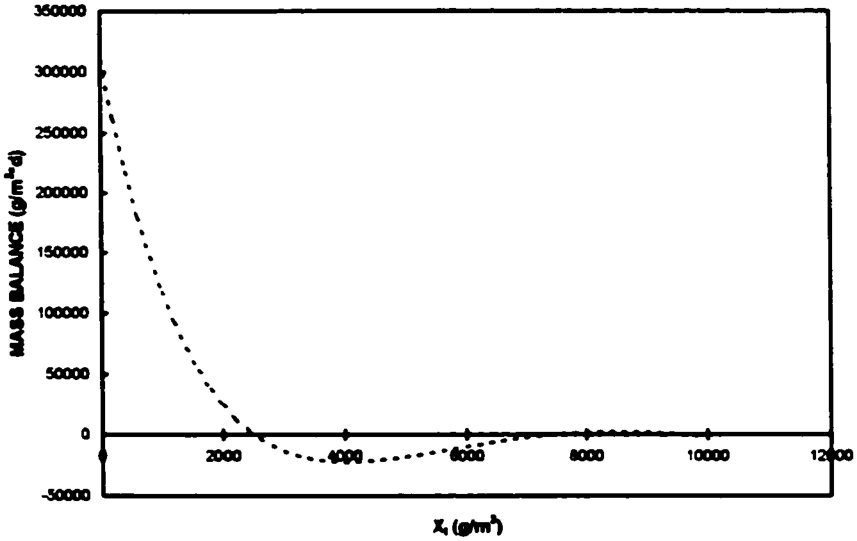

Figure 6.3: Solution plot for Case 2 above feed layer (X_{i-1} = 2,000 mg/L, X_{i+1} = 3,000 mg/L).

Case 3 is the situation where there are solids above the feed layer, but no concentration gradient exists, i.e. X_{i-1} = X_{i+1} = 2,000 mg/L. The solution plot for Case 3 with "good" settling solids and an overflow rate of 16 m/d is shown in Figure 6.4.

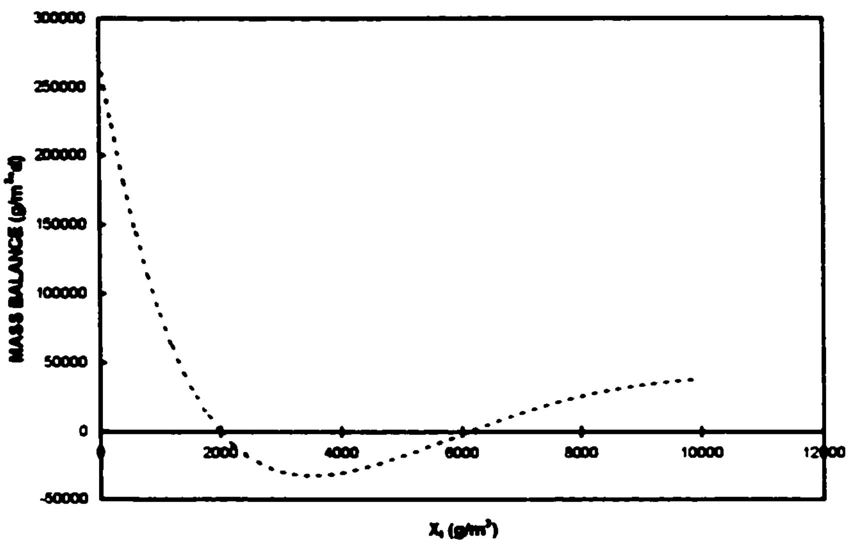

Figure 6.4: Solution plot for Case 3 above feed layer (X_{i-1} = X_{i+1} = 2,000 mg/L with "good" settling sludge).

Figure 6.4 shows that for this case the problem of multiple solutions occurs once again. Two solutions exist, only one of which is correct (X_i = 2,000 mg/L). Because of the multiple solutions, this case would be sensitive to the initial value used in the solution procedure. Similar results to Figure 6.4 were found until the overflow rate was increased to approximately 22 m/d, beyond which only the correct solution existed. When "poor" settling sludge was used, even less desirable results were obtained. Figure 6.5 shows the solution plot for Case 3 with "poor" settling sludge and an overflow rate of 16 m/d. Three solutions to the mass balance equation exist, only one of which is correct (X_i = 2,000 mg/L). One of the incorrect solutions (X_i =2, 248 mg/L) lies very close to the correct solution, so in Case 3 if "poor" settling sludge is used the solution is extremely sensitive to the initial guess. This behaviour with "poor" settling sludge was observed until the overflow rate was increased beyond 21 m/d; above this overflow rate only the correct solution exists.

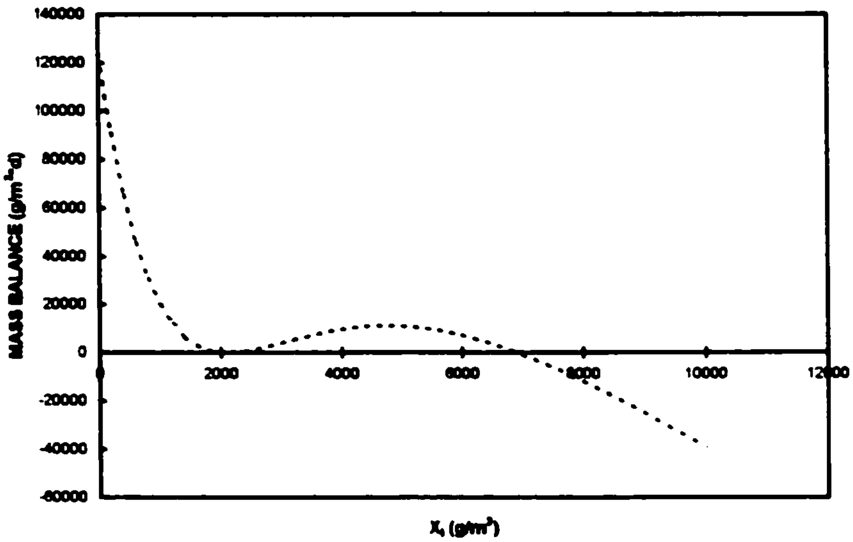

Figure 6.5: Solution plot for Case 3 above feed layer (X_{i-1} = X_{i+1} = 2,000 mg/L with "poor" settling sludge).

Solution Behaviour Of Feed Layer

The solution behaviour of the feed layer equation also was investigated in a manner similar to that used to investigate the region above the feed layer. For both "good" and "poor" settling sludges over a range of overflow and underflow rates (i.e. recycle ratios of 0.5, 1, and 2) and feed concentrations, the mass balance equation for the feed layer showed stable solution behaviour. Multiple solution cases such as those seen for the region above the feed layer were not encountered.

Solution Behaviour Below Feed Layer

The first case investigated a settling tank scenario where a concentration gradient has formed below the feed layer with X_{i-1} = 5,000 mg/L and X_{i+1} = 6,000 mg/L. The solution plot for Case 1 with "good" settling solids and an underflow rate of 32 m/d is shown in Figure 6. 6. For these conditions the mass balance equation in the region below the feed layer can also be prone to the types of multiple solution problems seen earlier in the region above the feed layer. In this case, there are three solutions very close to one another (X_i = 5,000 mg/L, X_i = 5,566 mg/L, X_i = 6706 mg/L). At higher underflow rates, multiple solutions continued to exist, but these were not as close together. When "poor" settling biosolids were used for this case, multiple solutions also were encountered, with only the one where $X_i = X_{i-1}$ making sense. In this case, two of the solutions possibly are feasible.

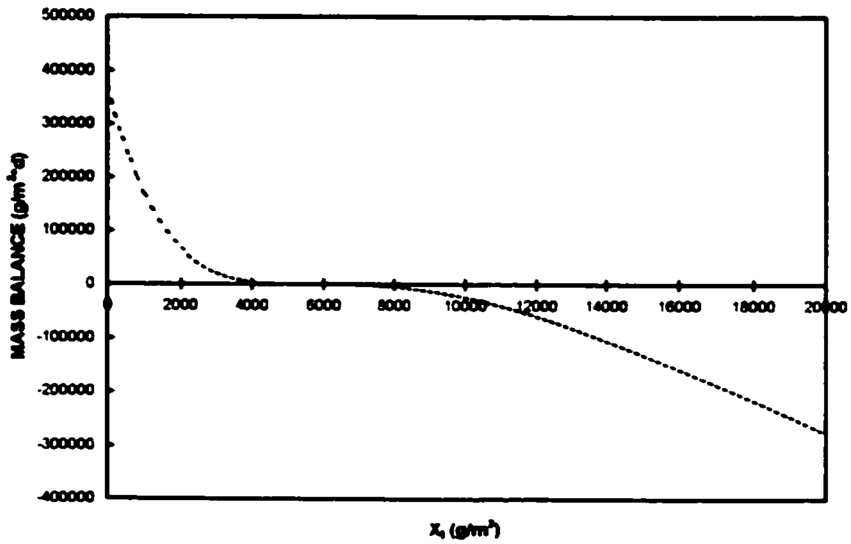

Figure 6.6: Solution plot for Case 2 below feed layer (X_{i-1} = 5,000 mg/L, X_{i+1} = 6,000 mg/L).

The second case investigated below the feed layer was the situation where no concentration gradient exists, e.g. $X_{i-1} = X_{i+1}$ = 8,000 mg/L. For both "good" and "poor" settling sludges, multiple solutions were found to exist at some underflow rates, but in both situations, solutions that did not violate the concentration profile (i.e. X_i = 8,000 mg/L) were obtainable.

DISCUSSION OF FINDINGS FOR STEADY STATE CASES

Based on the examination of the steady state solution behaviour of the one-dimensional mass balance equations for the three regions in a secondary settling tank, several conclusions may be drawn. In the layers above and below the feed point, cases were seen where multiple solutions existed for both "good" and "poor" settling sludges. Cases were also observed where only non-sensible solutions existed for "poor" settling sludges. The feed layer seemed to be far more robust; multiple solutions were not observed under any of the loading conditions. A further difficulty in certain cases is that the mass balance function is particularly "flat" in the region of the solution, and an iterative numerical solution procedure likely will encounter difficulties finding the root.

The results show that it may be very difficult to develop a one-dimensional secondary settling tank model capable of giving true "steady state" solutions. Depending on the loading conditions of the settling tank (i.e. under-loaded, critically loaded, or over-loaded) and the sludge settling characteristics, attempting to solve the system of "steady state" mass balance equations may result in a non-sensible solution, or problems may be encountered because of multiple solutions.

UNSTEADY STATE CASE FOR A BATCH SETTLING TEST

The simplest application of one-dimensional settling tank modelling is in the simulation of a batch settling test on a sample of mixed liquor which exhibits zone settling characteristics, and where there is no restriction on the maximum sludge compactability at the base of the settling column. If the settling column is divided into layers, mass balance equations may be written for each layer. Taking into account the boundary conditions for the top layer (i.e. no solids flux into the layer) and the bottom layer (i.e. no solids flux out of the layer), the following equations for the solids concentrations in the various layers of the settling column may be developed:

$$X_1^{n+1} = X_1^n - \frac{\Delta t}{\Delta z}\left\{X_1^n \cdot V_0 e^{-KX_1^n}\right\} \qquad \text{(top layer)} \qquad (5)$$

$$X_i^{n+1} = \frac{\Delta t}{\Delta z}\left\{X_{i-1}^n \cdot V_0 e^{-KX_{i-1}^n} - X_i^n \cdot V_0 e^{-KX_i^n}\right\} + X_i^n \qquad \text{(middle layers)} \qquad (6)$$

$$X_m^{n+1} = X_m^n + \frac{\Delta t}{\Delta z}\left\{X_{m-1}^n \cdot V_0 e^{-KX_{m-1}^n}\right\} \qquad \text{(bottom layer)} \qquad (7)$$

where V_0 and K are the Vesilind parameters, Δt is the time step, Δz is the layer thickness, m is the total number of layers used, i is the space index, n is the time index, X_{i-1} is the TSS concentration in the layer above the solution layer, X_{i+1} is the TSS concentration in the layer below the solution layer, and X_i is the TSS concentration in the solution layer.

A batch settling test is simulated by integrating forward from t = 0, assuming a uniform initial concentration distribution throughout the settling column. An example of model output after a short period of time is shown in Figure 6.7. Figure 6.7 simulates a case where the sludge settling properties are "good", with an initial concentration of 3,000 mg/L in a 50 cm settling column. Intuitively, this type of model result indicates that this approach is valid. For example, we see a falling sludge - water interface with the passage of time, with thickening occurring in the bottom of the settling column. Notice that the definition of the sludge-water interface is coarse since only 10 layers were used in this simulation. A mass balance on the concentration profile shown in Figure 6.7 confirms that the mass balance is conserved. It perhaps should be noted here that the goal of these simulations is to investigate whether the expected settling behaviour can be simulated. No attempts will be made to calibrate or validate the models with actual settling data since this exercise is beyond the scope of this study.

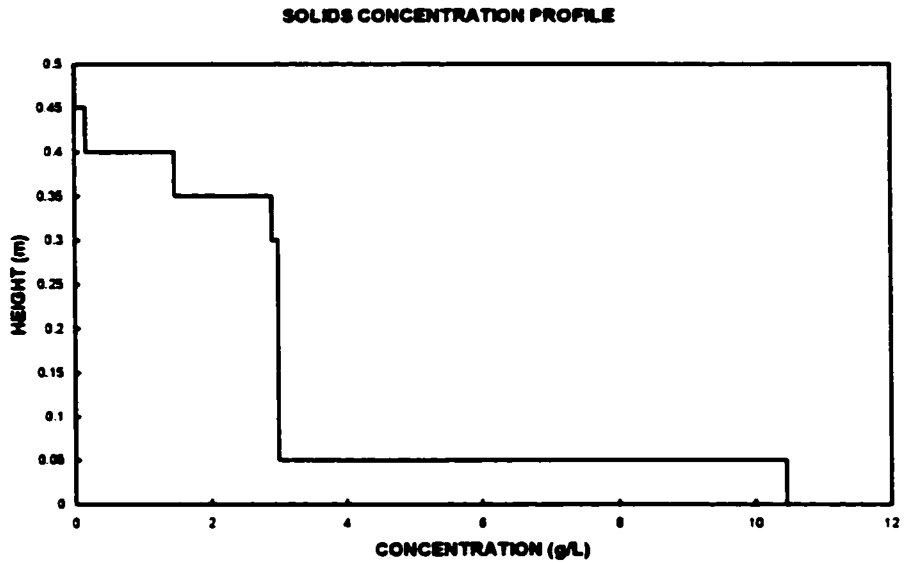

Figure 6.7: Sample output for simple layered model.

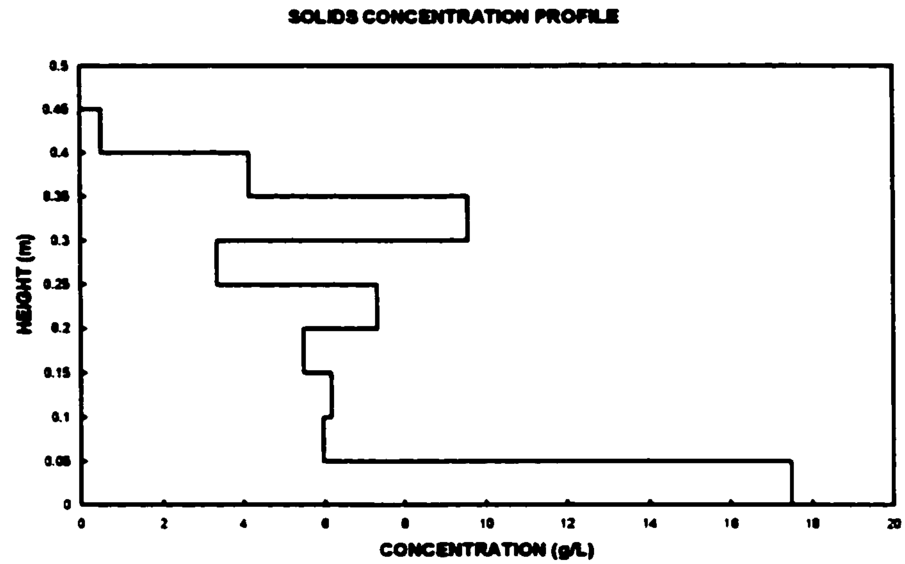

Figure 6.8: Instabilities in layered model output.

Solution problems also can be encountered in simulating the time-dependant behaviour in a batch settling test. For example, depending on the initial concentration and the settling properties of the sludge, the model may show instabilities. An example of this behaviour is shown in Figure 6.8. After a short period into the batch settling test the predicted behaviour is not as expected. Instead of a falling sludge-water interface with the passage of time, the model exhibits instabilities with solids becoming "trapped" in the upper layers of the settling column. This problem may be rectified to a certain degree by increasing the resolution of the column discretization by increasing the number of layers used and using smaller time step values. However, even with these actions, it is still possible to obtain highly unstable model predictions, as shown in Figure 6.9. The reasons for this behaviour become apparent upon further examination of the approach used in the simple layered mass balance approach.

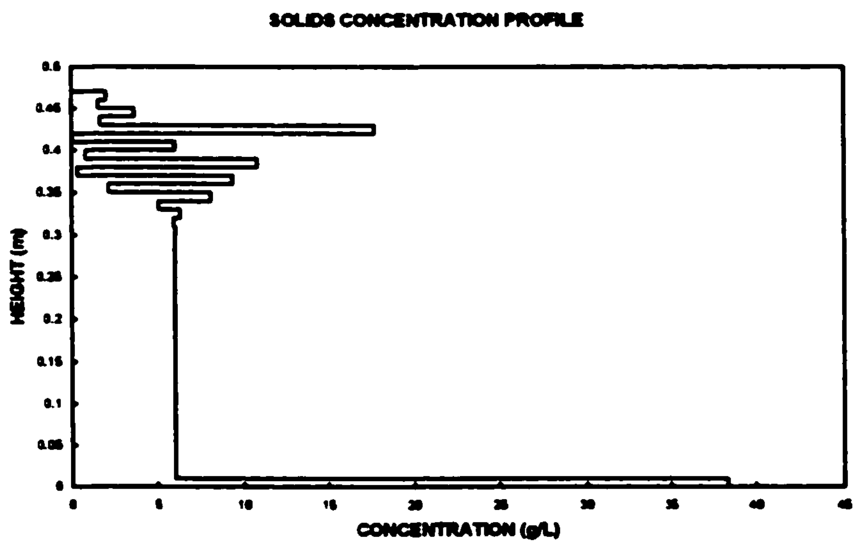

Figure 6.9: Instabilities in highly discretized (50 layers) model output.

Figure 6.10 below shows the development of instabilities under certain initial conditions for the batch settling test:

1. Initially, all layers in the settling column are at the same concentration. Therefore, all layers are capable of passing the same solids flux, as shown on flux curve (A). When the first time step is taken, all layers pass and receive this same solids flux, except for the top and bottom layers. The top layer only passes flux, it does not receive it. The bottom layer only receives flux, it does not pass it. Essentially, the flux transferred out of the top layer is transmitted down through the column to the bottom layer.

2. Examining the top two layers after the first time step [shown on flux curve (B) in Figure 6.10], it is evident that the top layer has lowered in concentration and now is capable of passing more flux than the second layer, which remains at the initial concentration.

3. When the second time step is taken, the second layer increases to a concentration greater than the initial concentration because it receives more flux from the top layer than it is able to pass. Solids from the top layer become "trapped" in the second layer rather than being transmitted down through the column to the bottom layer, as shown on flux curve (C) in Figure 6.10.

4. With further time steps, the problem is exacerbated because the top layer continues to pass a greater amount of flux than the second layer as its concentration decreases while the second layer concentration continues to increase because it is receiving solids faster than it can transmit them.

5. After a few more time steps, model instabilities manifested as "trapped" solids are seen in the upper layer. Another consequence of this behaviour is that because solids become trapped in the uppermost layers, intermediate layers begin to lower in concentration and we see the same process occur throughout the settling column in "chain-reaction" fashion.

The unstable behaviour is not seen for lower initial concentrations (less than the concentration corresponding to the maximum in the flux curve). This can be understood by referring to Figure 6.11, and following the same step-wise logic. At each integration step a lower layer receives less flux from the layer above than it is capable of passing, so there is a net decrease in mass in the second layer. That is, solids from the upper layers continue to be transmitted down through the column to the bottom layer, and there is no "trapping" of solids in the upper layers as seen in the unstable case.

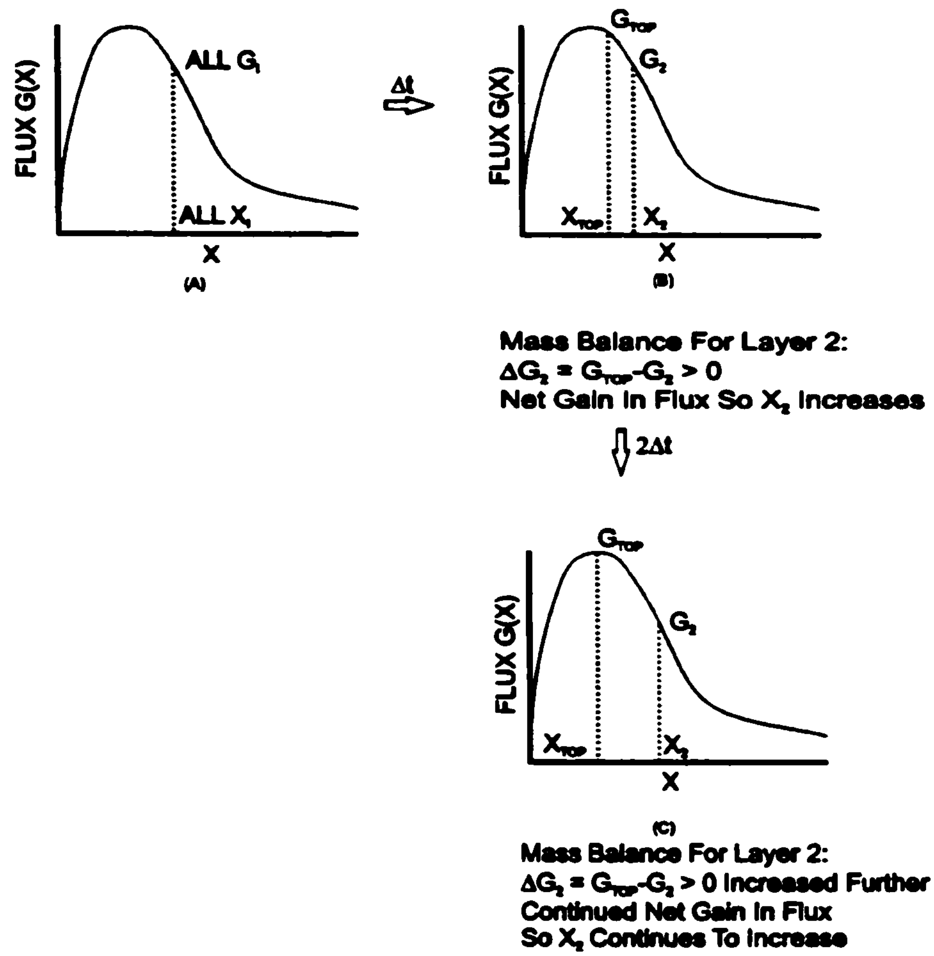

Figure 6.10: Propagation of instabilities in batch settling simulation.

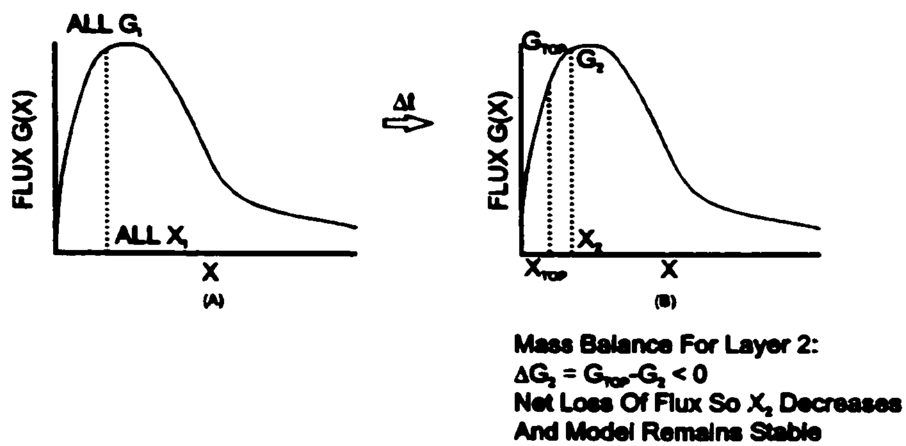

Figure 6.11: Explanation of stable model behaviour.

MODEL ADAPTATIONS TO ADDRESS STABILITY PROBLEMS

The examples in the preceding sections illustrate different problems associated with the application of one-dimensional layered settling models. The section on steady state solutions for continuous flow settlers demonstrated possible problems of:

- Multiple solutions to the mass balance equations; and
- Numerically difficult-to-solve mass balance equations because the equations can be "flat" in the region of the solution.

The section on dynamic simulation of batch settling behaviour demonstrated possible problems of numerical instability. Researchers have proposed a number of approaches to overcome the numerical problems. These generally have been applied to the case of dynamic response in continuous flow settlers rather than the steady state case, and the simple case of batch settling has not been considered.

An approach that appears to have gained wide acceptance, and which is applied in a number of commercial treatment plant simulation packages, is to limit the settling flux into a layer such that it does not exceed the settling flux out of that layer (Vitasovic, 1989). For example, with this constraint Eq. 4 for a layer *i* below the feed layer becomes:

$$V_{DN}\left(X_{i-1}-X_i\right)+\min\left(V_0 e^{-KX_{i-1}}\cdot X_{i-1}, V_0 e^{-KX_i}\cdot X_i\right)-\min\left(V_0 e^{-KX_i}\cdot X_i, V_0 e^{-KX_{i+1}}\cdot X_{i+1}\right)=0 \qquad (8)$$

As shown here, the constraint is applied to the *settling* flux only. [Literature references often state that the constraint applies to the total flux (bulk plus settling flux) but in fact only apply the constraint to the settling flux term]. Härtel and Pöppel (1992) and Otterpohl and Freund (1992) multiply the settling flux "min" terms by an empirical correction factor, Ω, which reduces from 1 slightly below the feed layer to zero at the bottom layer. Takacs et al. (1991) applied the settling flux constraint, and added a further constraint that limits the settling velocity to a fixed maximum value in the 200 to 2,000 mg/L concentration range.

These settling flux constraint approaches do resolve numerical problems in many cases. The effect is to force a solution where the concentration of a certain layer is lower than that of the layer below. However, it should be recognised that this approach of disregarding or overriding the settling model equations may result in solutions that are misleading and not realistic. The fact that the approach reduces numerical problems should not be seen as providing correct solutions.

Anderson (1981), Hamilton et al. (1992) and Ozinsky (1994) use an alternative approach, adding a second order eddy diffusivity term to the layer mass balance equation. This serves to reduce the gradient of the shock wave front, and the numerical problem becomes more stable. In a sense it can be argued that introducing the diffusivity term attempts to account for real hydrodynamic effects. Alternatively the diffusivity coefficient can be regarded merely as an additional settling model calibration parameter. Again there is the danger that the diffusivity term may force an incorrect solution (in terms of the flux settling equation) merely by outweighing the mass flux terms. However, this approach holds the distinct advantage that it does not disregard the basic settling model. Also, the effect of the diffusivity term should be restricted mainly to the region of the water-sludge interface (where the concentration gradient is greatest).

CONCLUSIONS

One-dimensional settling tank models are useful in the simulation of coupled activated sludge reactor-settler systems. However, solution of the model equations can pose problems. It is suggested that the diffusivity term approach is to be preferred to the flux constraint approach. It is further suggested that, in evaluating model modifications to overcome numerical stability problems, the modifications initially should be evaluated for the case of a simple batch settling test.

Aside from the modeling difficulties discussed above, a further concern with the simple 1-D modeling approach is that no limitation is imposed on the maximum sludge concentration in the compaction zone. For example, simulating a batch settling test case with X_0 = 3,000 mg/L with a 10 layer model, the final concentration in the bottom layer after settling is complete would be 30,000 mg/L. In practice, there will be some limit on the maximum sludge compactability (probably in the range of 10,000-20,000 mg/L). This aspect should be incorporated into any modeling approach (1, 2, or 3-D). This constraint can be very important in determining the distribution of solids between the reactors and settler in coupled systems as well as the concentration profile within the settler. Overlooking this physical limitation in modeling system behaviour can result in very misleading simulation results.

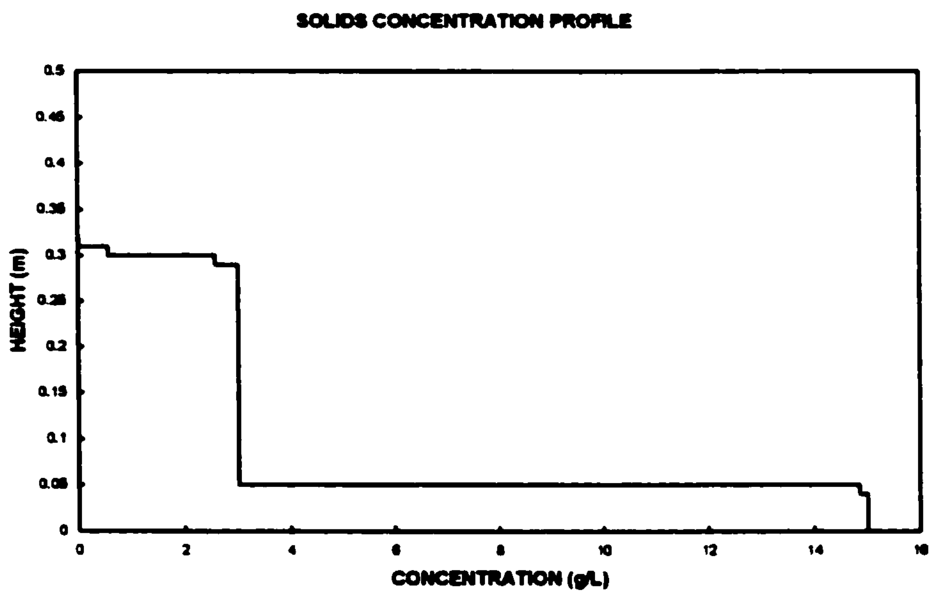

Figure 6.12: Model output for approach incorporating maximum allowable concentration of sludge.

Figure 6. 12 was generated by simulating a column settling test for a sludge with good settling properties at an initial concentration of 3,000 mg/L. The column was discretized into 50 layers. Figure 6.12 shows that under these conditions the model behaves quite well. Several key features of this approach should be noted from Figure 6.12. First, because of the fine spatial and temporal discretization used, the resolution of the sludge-water interface is fairly good. Also, Figure 6.12 shows that incorporating the maximum allowable concentration has the desired effect. The bottom layers have been allowed to increase to the user-specified value of 15,000 mg/L, and they have been stopped there.

Figure 6.12 also shows how the layer above the region of maximum concentration is increasing in concentration thus propagating the region upward simultaneously to the falling sludge-water interface.

REFERENCES

Anderson, H.M. (1981) A dynamic simulation model for wastewater renovation systems. Ph.D. dissertation, Wayne State University, Detroit, Michigan, USA.

Hamilton, J., Jain, R., Antoniou, P., Svoronos, S.A., Koopman, B., and Lyberatos, G. (1992) Modeling and pilot-scale experimental verification for predenitrification process. J. Environ. Engng., ASCE 118 (1), 38-55.

Härtel, L., and Pöpel, H.J. (1992) A dynamic secondary clarifier model including processes of sludge thickening. Wat. Sci. Tech., 25, 267.

IAWQ - Ekama, G.A., Barnard, J.L., Gunthert, F.W., Krebs, P., McCorquodale, J.A., Parker, D.S. and Wahlberg, E.J. (1997) Secondary settling tanks: theory, modelling, design and operation. Scientific and Technical Report No. 6, International Association on Water Quality, London, England.

Jeppsson, U. (1996). Modelling aspects of wastewater treatment processes. Ph.D. dissertation, Department of Industrial Electrical Engineering and Automation, Lund Institute of Technology, Lund, Sweden.

Metcalf and Eddy (1991). Wastewater engineering: treatment, disposal, and reuse. 3rd edition, McGraw Hill, Toronto.

Otterpohl, R. and Freund, M. (1992). Dynamic models for clarifiers of activated sludge plants with dry and wet weather flows. Wat. Sci. Technol., 26, (5/6), 1391-1400.

Ozinsky, A.E., Ekama, G.A., and Reddy, B.D. (1994). Mathematical simulation of dynamic behaviour of secondary settling tanks. Research report W85, University of Cape Town, South Africa.

Takács, I., Patry, G.G., and Nolasco, D. (1991). A dynamic model of the clarification-thickening process. Water Research, 25, (10), 1263-1271.

WRC - Water Research Commission of South Africa. (1984). Theory, Design and Operation of Nutrient Removal Activated Sludge Processes. Water Research Commission, P.O. Box 824, Pretoria 0001, South Africa.

Vitasovic, Z.Z. (1989). Continuous settler operation: a dynamic model. In Dynamic modelling and expert systems in wastewater engineering. (ed. G.G. Patry and D. Chapman), pp, 59-81. Lewis, Chelsea.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 OVERVIEW

This research set out to investigate aspects of sludge settleability measurement and one-dimensional settler models. Quantification of sludge settleability is crucial for settling tank design and operation. This usually is done via an empirical relationship that is based upon the assumption that the major factor influencing settling velocity in a zone settling regime is solids concentration. Parameters used in these relationships require measurement of sludge zone settling velocity in column settling tests over a wide range of concentrations. Due to the extensive experimental effort involved, several alternative measures (e.g. SVI, DSVI, SSVI) have gained favour for monitoring sludge settleability at full-scale treatment facilities. These SVI-type measures were not created initially with the intention of being used as a means for quantifying the relationship between solids concentration and sludge settling velocity; rather, they were intended as an empirical means of monitoring sludge settleability on a day to day basis at a treatment facility. A simple model was developed in order to investigate artifacts researchers have attributed to SVI-type measures over the years. Problems with numerical stability of one-dimensional layered settling tank models were investigated for the steady state continuous flow and unsteady state batch settling cases.

7.2 CONCLUSIONS

Conclusions from this research are grouped according to those related to SVI-type measures and one-dimensional layered settling tank models.

7.2.1 SVI-type Measures

- The SVI model developed in this research provides a simple, yet elegant, means for interpreting settling test behaviour. The model serves as a tool to demonstrate the interactive impact of test column height, biosolids concentration and compactability, and zone settling characteristics on SVI results. It is *expected* that SVI will vary with solids concentration.

- Depending on the test conditions (column height, biosolids settleability and compactability), SVI may show a marked dependence on the biosolids concentration. Cases were observed where the SVI changed threefold from 50 to 160 mL/g if the test was performed at a biosolids concentration of 1.8 or 3.8 g/L, respectively.

- The settling column height impacts the SVI. This is not through impacting settleability *per se*; rather, it is merely a calculation artifact.

- The DSVI test "forces" the SVI test conditions into the region where SVI is independent of solids concentration. Intuitively it may seem that this is a suitable measuring state. However, in this region the observed SVI bears no relation to the settleability of the test sample. Rather, the DSVI only provides a measure of biosolids compactability.

- It has been demonstrated that DSVI is directly linked (and inversely related to) the biosolids compactability parameter. A biosolids sample with extensive filamentous bulking would be characterized by a poor compactability, and hence a high DSVI. The same link is not true necessarily for SVI, depending on the measuring regime. Cases observed showed that for tests conducted on samples with different compactabilities (and likely different extents of bulking), the SVI value is the same. This indicates that SVI *per se* is not necessarily a good measure for monitoring bulking. Rather, DSVI possibly should provide a preferable means for quantifying bulking.

- The model was used as a basis for evaluating proposed correlations for estimating zone settling velocity parameters based on SVI-type measures. The overall conclusions from the comparison is that (1) there are significant differences between the predicted V_0 and K values from the different correlations; and (2) the predicted values generally are not in good agreement with the "true" values. The ZSV obtained via the correlations generally is not in good agreement with the "true" ZSV, and there is a wide variation in predictive capacity for each correlation depending on the conditions for measuring SVI. A consequence of differences between predicted and "true" ZSV parameters when applied in flux theory analysis is significant differences in maximum allowable overflow rate. These results strongly question whether a measure at one concentration can tell us how concentration influences settleability.

- The research questions the validity of the correlations for zone settling parameters based on DSVI or SVI. With regard to DSVI, it is evident that two samples with very different zone settling parameters (V_0 and K) very possibly could have the same DSVI. However, a correlation based on DSVI will predict the same V_0 and K. With regard to SVI, the results show that a sample with given zone settling parameters (V_0 and K) can exhibit a wide range of SVI values even for small variations in concentration in the test. However, a correlation based on SVI will predict widely different pairs of V_0 and K values.

- If the SVI test is conducted according to the procedure outlined in *Standard Methods* (since 1980) [i.e. with stirring] then SVI (*Sludge* Volume Index) and SSVI (Stirred *Specific* Volume Index) procedures are equivalent. However, there appears to be a misconception that SVI and SSVI are different measures. This probably has arisen because SVI tests often continue to be performed according to the pre-1980 method without stirring. To avoid confusion it is suggested that the SVI test with and without stirring should be designated as sSVI and uSVI, respectively. The term sSVI itself may lead to confusion (with SSVI); however, this should not pose a problem as these are the same (aside from possible differences in the apparatus). Whenever SVI-type data are reported, the dimensions of the settling vessel also should be reported.

- The database of information on SVI-type measures is not consistent. For example, a set of SVI measures in a 1 L cylinder cannot be compared to SVI results from tests conducted in 6 foot settling columns. This likely is a reason why Ozinsky and Ekama (1995) found that certain sets of data from different researchers could not be pooled on a statistical basis.

7.2.2 One-Dimensional Layered Settling Tank Models

- Examination of the steady-state case for a continuous flow settling tank revealed that even when only three layers are considered, numerical solution problems may occur.

- For the steady-state continuous flow case, the numerical solution problems occur in the form of (1) multiple solutions [in some cases these multiple solutions all exist in a very narrow region]; and (2) the mass balance function being particularly "flat" in the region of the solution.

- The occurrence and severity of numerical solution problems for the steady-state continuous flow case are influenced interactively by settler operating conditions (e.g. upflow and downflow velocity, feed concentration) and sludge settleability.

- For the unsteady-state batch settling case, initial conditions were found to have a significant impact on whether a stable solution could be obtained without the imposition of settling flux restrictions. This behaviour can be explained through examination of the settling flux curve.

- For the unsteady-state batch settling case, increasing the spatial discretization does not aid in reducing numerical instability for certain initial conditions.

- When attempting to formulate dynamic models of continuous flow settling tanks, many researchers impose restrictions on the *settling flux* into a layer. It is the opinion of this researcher that these models should instead focus on the *total flux* into a layer, as this reflects what is actually happening in a settling tank.

7.3 RECOMMENDATIONS FOR FURTHER RESEARCH

The research in this thesis has investigated many aspects of sludge settleability. Further possible avenues of research include:

- The explanation of the effect of column height on SVI-type measures would be strengthened by performing more experimental work where settling tests are conducted simultaneously on the *same* sludge sample at the *same* concentration in columns of varying heights.
- The proposed method in Chapter 5 for obtaining V_0 and K from a series of SVI measures needs to be thoroughly tested and perhaps refined.
- Seeding algorithms need to be developed and studied in an effort to eliminate the numerical solution problems observed in the steady-state case for a continuous flow settling tank.
- For dynamic settling tank models, the research focus needs to move away from approaches which place restrictions on the settling flux into a given layer. Rather, research needs to focus more on approaches that do not require such restrictions in order to obtain a numerically stable solution.

7.4 CONTRIBUTION TO KNOWLEDGE

The objective of this research was to investigate aspects of sludge settleability including settleability measures and one-dimensional settling tank modelling. In addressing this objective, the research contained in this thesis makes a contribution to the knowledge through an increased understanding of issues related to sludge settleability. These include:

- The effect of solids characteristics and test parameters on SVI-type measures were demonstrated. The dependence of SVI on solids concentration which had previously been referred to only as an "artifact" was explained clearly. Other effects such as column height and maximum sludge compactability (and their interaction with solids concentration) which previously had not been documented clearly and definitively were explained using a mechanistic model as a basis.

- The relationship between the SVI and the DSVI was noted and explained rationally. The use of the model showed that the DSVI is not truly a measure of sludge settleability; rather, it is more closely related to maximum sludge compactability.

- Caution is recommended with regard to the use of correlations between SVI-type measures and parameters from empirical relationships (e.g. the Vesilind relationship) which attempt to quantify the influence of solids concentration on sludge settling velocity. Several cases are illustrated where the blind use of these correlations could lead to incorrect results, and the approach of attempting to explain the variability of sludge settling velocity over a range of concentration with *one* measurement at *one* concentration is strongly questioned.

- The issue of standardisation in settleability test procedures, apparatus, and nomenclature is raised. For example, the fact that the SVI continues to be performed in practice without stirring despite the fact that *Standard Methods* has called for stirring in the test for nearly twenty years indicates that this is an area which needs attention. Recommendations for new nomenclature and reporting procedures have been given in the thesis.

- Most of the literature in the area of settling tank modelling focuses on dynamic models. This research has shed light on the less-researched steady-state case and illustrated some of the numerical solution problems that can plague this approach.

- For the dynamic case, the simplified approach of modelling a batch settling test was used to provide a straightforward explanation of the numerical instabilities observed (yet not practically explained) by many researchers.

ADDITIONAL REFERENCES

(References for Chapter 2 and Appendices)

Chapman, D. (1984). The influence of dynamic loads and process variables on the removal of suspended solids from an activated sludge plant. Ph.D. dissertation, University of Alberta, Edmonton, Alberta, Canada.

Diehl, S. (1995a). Conservation laws with application to continuous sedimentation. Ph.D. dissertation, Department of Mathematics, Lund Institute of Technology, Lund, Sweden.

IAWQ - Ekama G.A., Barnard J.L., Gunthert F.W., Krebs P., McCorquodale J.A., Parker D.S. and Wahlberg E.J. (1997) Secondary settling tanks: theory, modelling, design and operation. Scientific and Technical Report No. 6, International Association on Water Quality, London, England.

Jeppsson, U. (1996). Modelling aspects of wastewater treatment processes. Ph.D. dissertation, Department of Industrial Electrical Engineering and Automation, Lund Institute of Technology, Lund, Sweden.

Krebs, P. (1991a). The hydraulics of final settling tanks. *Wat. Sci. Tech.*, **23**, 1037-1046.

Lee S.-E., Koopman B., Bode H. and Jenkins D. (1983) Evaluation of alternative sludge settleability indices. *Water Research* 17, 1421-1426.

Stenstrom (1975). A dynamic model and computer compatible control strategies for wastewater treatment plants. Ph.D. dissertation, Clemson University, Clemson, South Carolina, USA.

Takács, I., Patry, G.G., and Nolasco, D. (1991). A dynamic model of the clarification-thickening process. Water Research, 25, (10), 1263-1271.

Tracy, K.D. and T.M. Keinath. (1973). Dynamic model for thickening of activated sludge. *AIChE Symposium Series*, **70**, (136), 291-308.

Vaccari, D.A. (1984). Modelling and simulation of compressive gravity thickening of activated sludge. Ph.D. dissertation, Rutgers University, New Brunswick, New Jersey, USA.

Vesilind, P.A. (1968b). Design of prototype thickeners from batch settling tests. *Wat. Sewage Wks*, **115** (July), 302-307.

Vitasovic, Z.Z. (1989). Continuous settler operation: a dynamic model. In Dynamic modelling and expert systems in wastewater engineering. (ed. G.G. Patry and D. Chapman), pp, 59-81. Lewis, Chelsea.

Wahlberg, E.J. (1987). Development of settling flux curves using SVI. M.Sc. (Environmental Systems Engineering) thesis, Clemson University, Clemson, South Carolina, USA.

Zhou, S. and J.A. McCorquodale. (1992b). Modelling of rectangular settling tanks. *J. Hydr. Eng.*, ASCE, **118**, (10), 1391-1405.

APPENDIX ONE

SAMPLES OF EXPERIMENTAL SETTLING DATA SETS

A1.1 INTRODUCTION

The purpose of this Appendix is to illustrate examples of settling data required to calculate X_M and generate model SVI curves. The first three data sets are taken from Wahlberg (1987) (in 173 cm settling columns), while the fourth and fifth sets were measured using mixed liquor drawn from a municipal sewage treatment plant in Dundas, Ontario (in 50 cm settling columns).

For each data set, the following items are presented:

- Table of raw interface height / time data.
- Plot of interface height *versus* time.
- Table of interface settling velocity / solids concentration.
- Plot of ln V_S *versus* initial solids concentration (for estimating V_0 and K).
- Table of thirty minute and estimated final settled height data.
- Plot of estimated final settled height *versus* initial solids concentration (for estimating X_M).
- Plot of calculated SVI (based on H_{30} for each initial concentration) and predicted SVI *versus* initial solids concentration.

The predicted SVI "curve" consists of two sections as discussed in Chapter 2; that is:

$$SVI = \frac{1000}{X_M} \qquad (mL/g) \qquad (A1.1)$$

[for lower concentrations where settling is complete before 30 minutes]

$$SVI = \frac{H_0 - \left\{V_0 e^{-KX_0} \cdot 0.5\right\}}{X_0 H_0} \cdot 1000 \qquad (A1.2)$$

[for higher concentrations where settling is not complete at 30 minutes]

A1.2 WAHLBERG RUN SC7

Table A1.1: Raw interface height *versus* time data for run SC7.

	Height (cm)					
Time (min)	X_0 = 1.8 (g/L)	X_0 = 2.7 (g/L)	X_0 = 3.6 (g/L)	X_0 = 4.8 (g/L)	X_0 = 7.1 (g/L)	X_0 = 9.5 (g/L)
0.0	173.0	173.0	173.0	173.0	173.0	173.0
7.5	[illegible]	137.0	124.8	166.5	171.6	173.0
10.0	114.5	120.0	[illegible]	158.9	170.5	172.0
12.5	92.5	104.0	104.2	150.9	169.0	171.8
15.0	70.0	89.0	95.2	144.6	167.0	171.5
20.0	41.7	67.9	80.1	131.7	162.9	[illegible]
22.5	37.9	61.7	73.7	126.1	161.0	[illegible]
25.0	35.0	57.9	68.3	120.2	159.2	168.6
27.5	32.9	53.2	63.7	115.0	157.5	168.0
30.0	31.0	50.2	60.0	109.9	155.6	167.3
35.0	28.4	45.5	53.6	100.9	152.2	[illegible]
40.0	26.5	42.0	49.2	93.9	148.8	[illegible]
45.0	25.0	39.7	45.5	88.4	145.5	162.5
50.0	23.7	37.8	42.7	83.9	141.5	161.1

Note: Shaded areas represent data used to determine interface settling velocity.

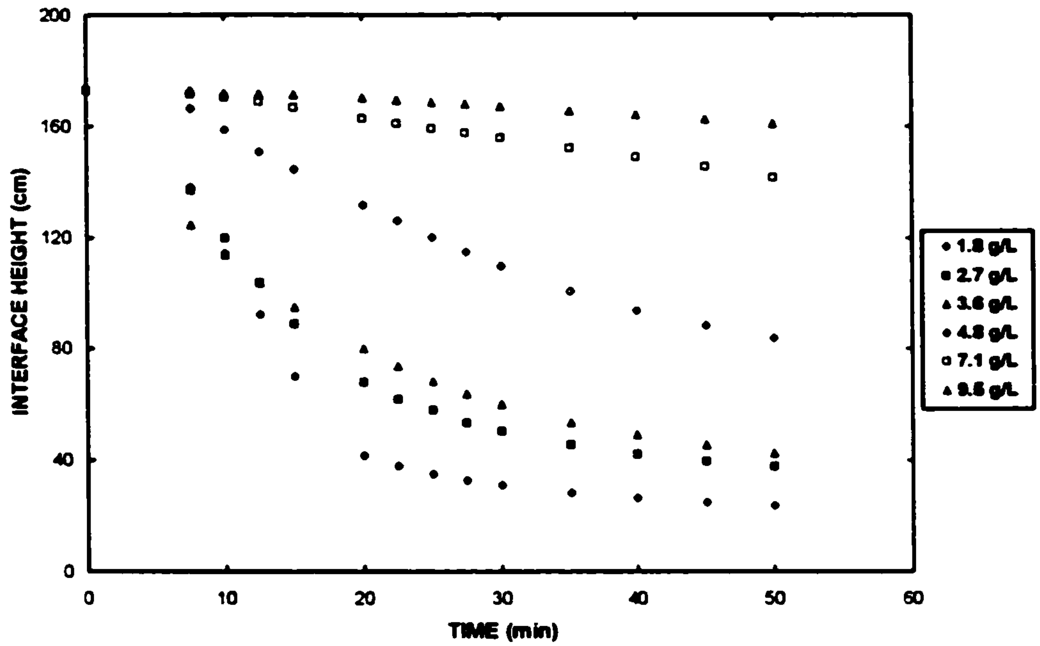

Figure A1.1: Interface height *versus* time for run SC7.

Table A1.2: Interface settling velocity data for run SC7.

X_o (g/L)	V_S (m/h)	ln V_S
1.8	5.42	1.69
2.7	3.84	1.35
3.6	2.37	0.86
4.8	1.48	0.39
7.1	0.42	-0.86
9.5	0.18	-1.69

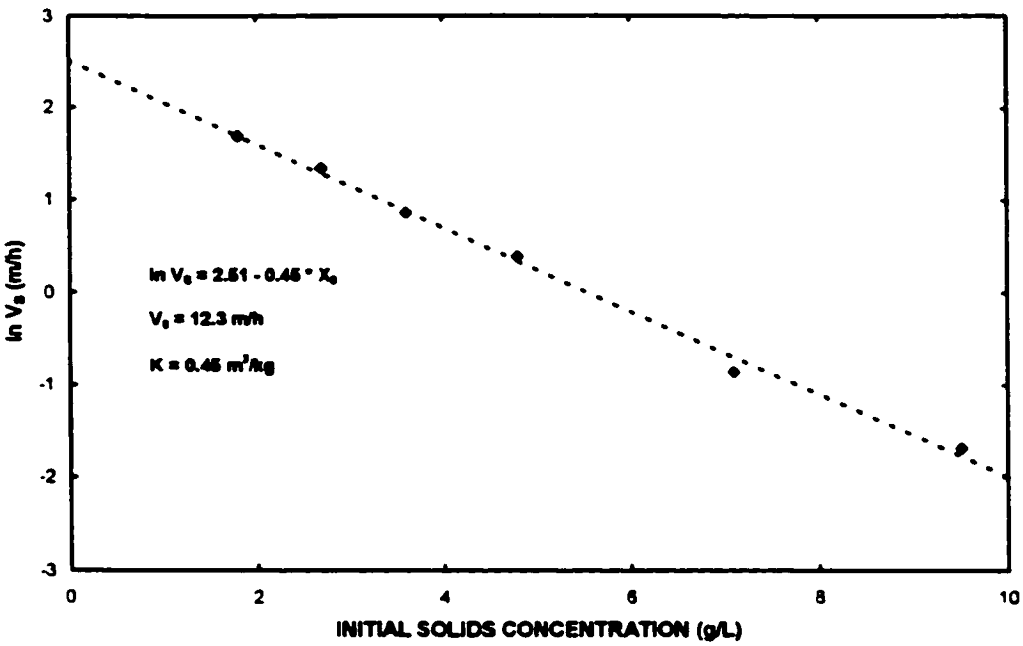

Figure A1.2: Interface settling velocity *versus* initial solids concentration for run SC7.

Table A1.3: Thirty minute and estimated final settled height data for run SC7.

X_0 (g/L)	H_{30} (cm)	H' (cm)	Final Settled Height Fraction	Calculated SVI (mL/g)
1.8	31.0	24.0	0.14	100
2.7	50.2	38.0	0.22	108
3.6	60.0	43.0	0.25	96
4.8	109.9	84.0	0.49	132
7.1	155.8	142.0	0.82	127
9.5	167.3	161.0	0.93	102

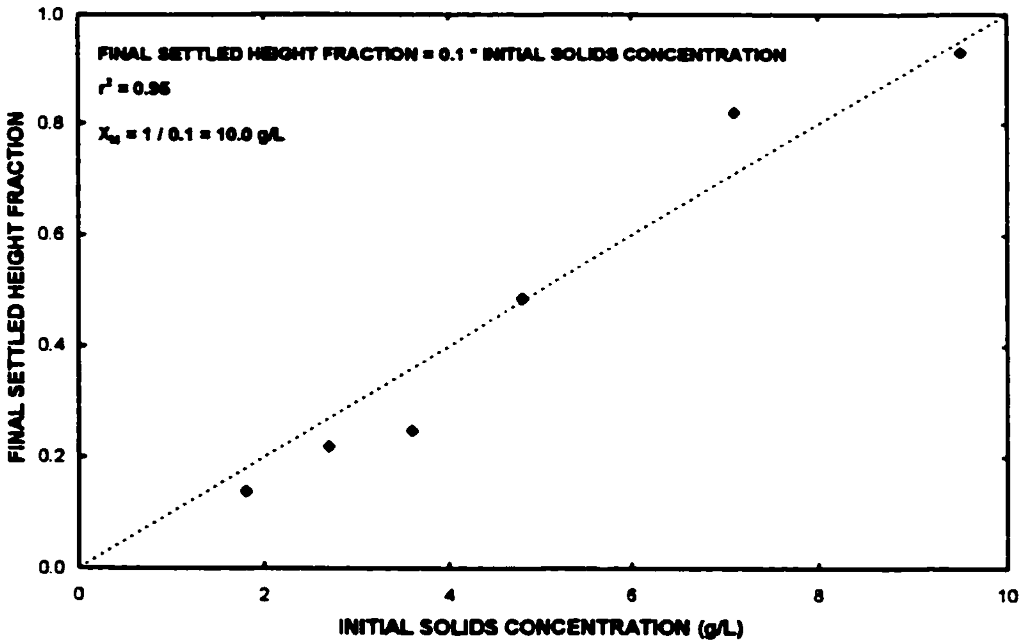

Figure A1.3: Estimated final settled height *versus* initial solids concentration for run SC7.

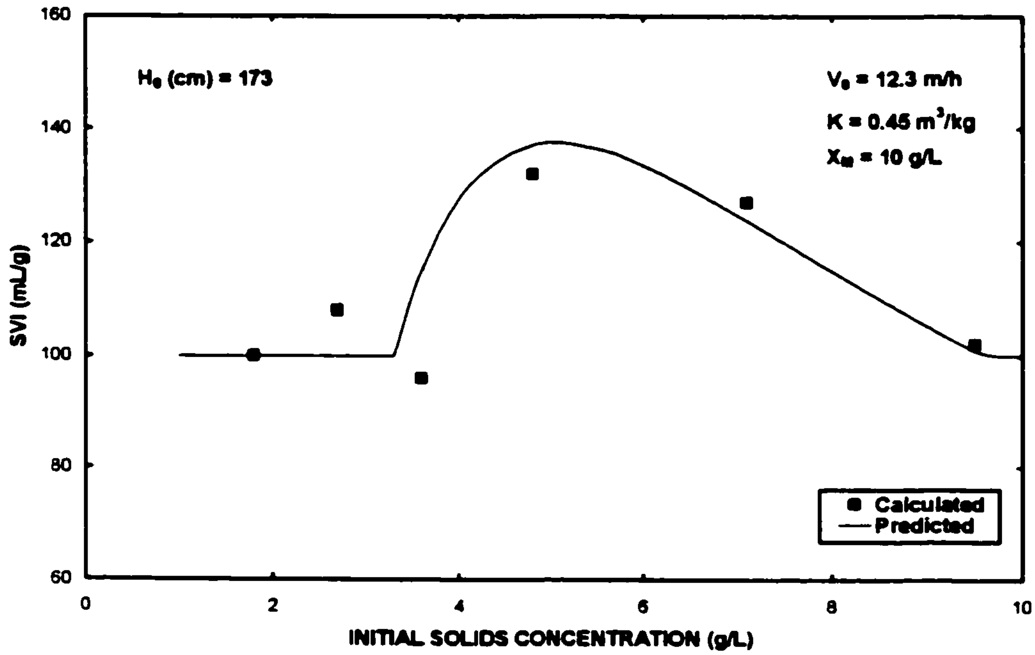

Figure A1.4: Calculated and predicted SVI *versus* initial solids concentration for run SC7.

A1.3 WAHLBERG RUN GA2

Table A1.4: Raw interface height *versus* time data for run GA2.

Time (min)	Height (cm) X_0 = 1.3 (g/L)	X_0 = 1.7 (g/L)	X_0 = 1.7 (g/L)	X_0 = 3.4 (g/L)	X_0 = 5.1 (g/L)	X_0 = 6.7 (g/L)
0.0	173.0	173.0	173.0	173.0	173.0	173.0
7.5	143.0	140.0	157.0	171.4	171.7	170.0
10.0	120.5	121.5	148.5	168.6	170.5	169.9
12.5	99.8	105.5	138.0	165.7	169.2	169.9
15.0	79.0	91.4	127.5	162.9	167.9	169.5
17.5	60.0	79.5	115.7	159.7	166.2	169.3
20.0	48.1	70.7	103.0	156.2	164.3	169.0
22.5	43.3	65.2	92.0	152.9	162.4	168.8
25.0	39.5	60.2	80.0	149.7	160.5	168.4
27.5	36.8	57.0	71.4	146.0	158.5	168.1
30.0	34.8	54.5	66.8	142.6	156.6	167.9
37.5	30.5	48.5	57.4	132.3	150.0	166.7
40.0	29.5	47.0	55.0	128.8	147.9	166.2
45.0	28.0	44.3	51.2	121.9	143.2	165.3

Note: Shaded areas represent data used to determine interface settling velocity.

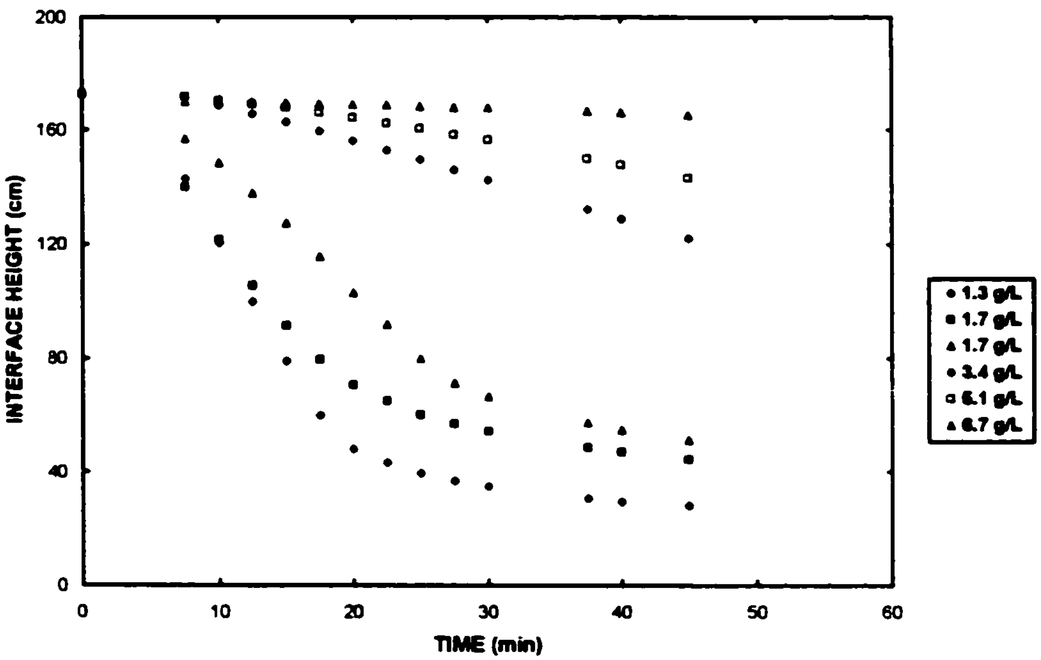

Figure A1.5: Interface height *versus* time for run GA2.

Table A1.5: Interface settling velocity data for run GA2.

X_0 (g/L)	V_S (m/h)	ln V_S
1.3	5.10	1.63
1.7	4.14	1.42
1.7	2.38	0.87
3.4	0.82	-0.20
5.1	0.50	-0.69
6.7	0.09	-2.39

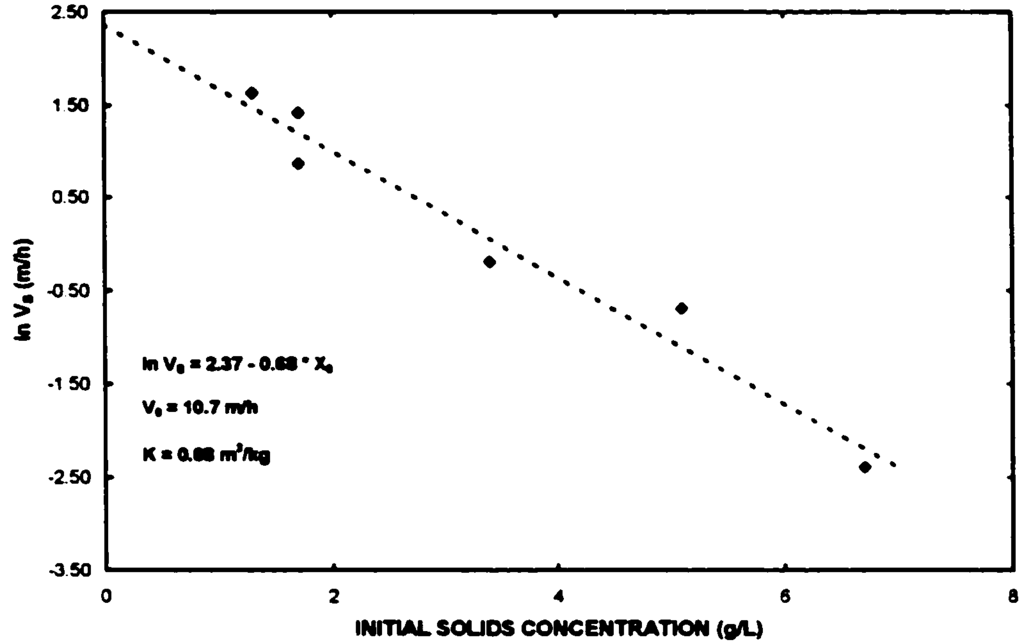

Figure A1.6: Interface settling velocity *versus* initial solids concentration for run GA2.

Table A1.6: Thirty minute and estimated final settled height data for run GA2.

X_0 (g/L)	H_{30} (cm)	H' (cm)	Final Settled Height Fraction	Calculated SVI (mL/g)
1.3	34.8	27.0	0.16	155
1.7	54.5	42.0	0.24	185
1.7	66.8	42.0	0.24	227
3.4	142.6	100.0	0.58	242
5.1	156.6	130.0	0.75	178
6.7	167.9	160.0	0.92	145

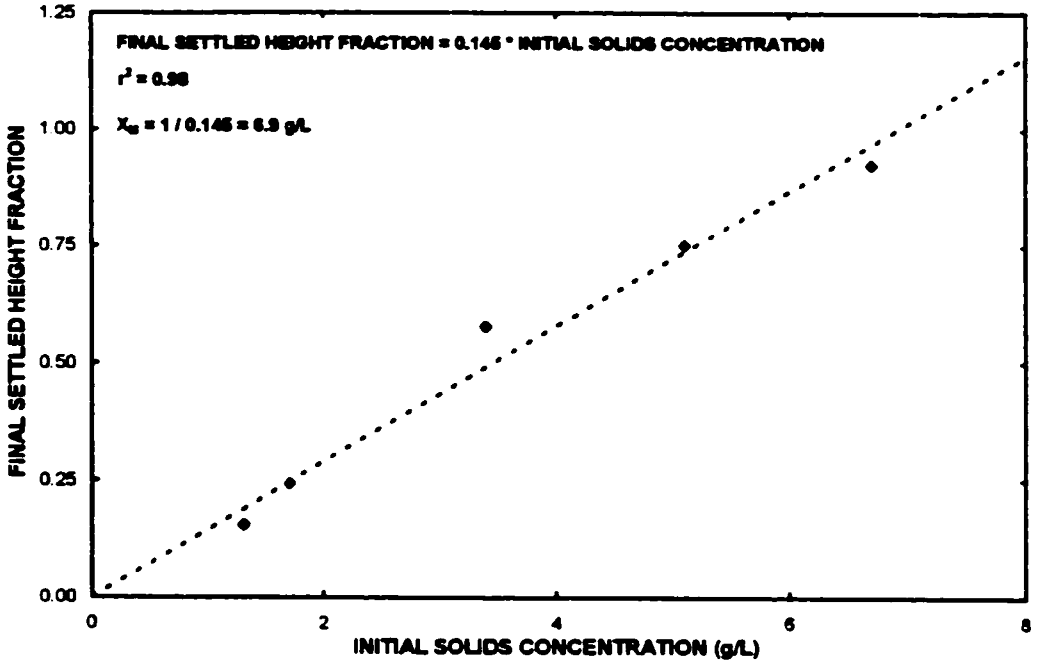

Figure A1.7: Estimated final settled height *versus* initial solids concentration for run GA2.

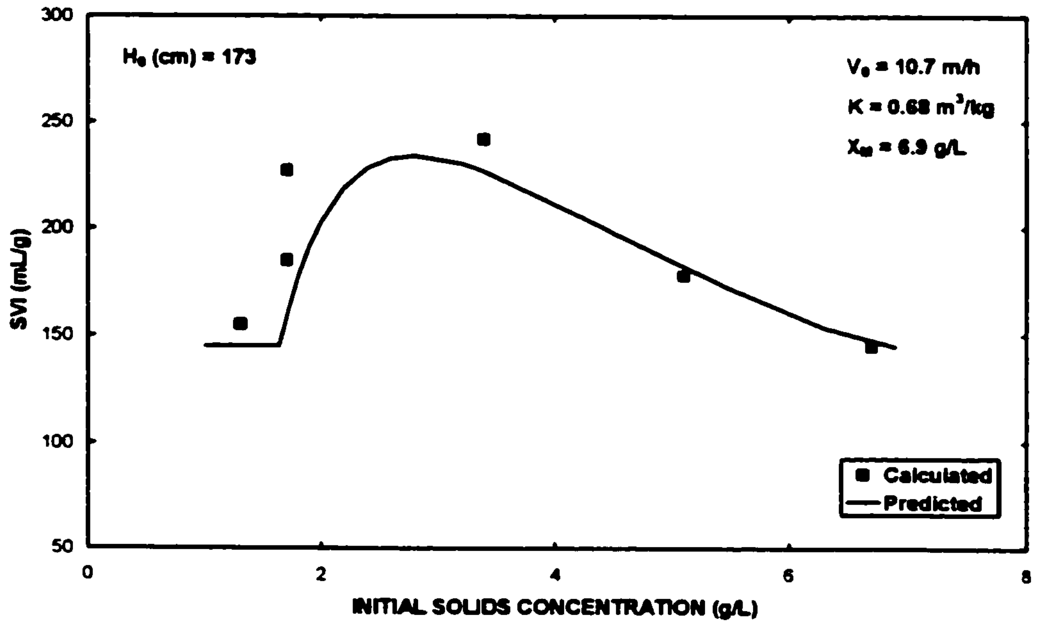

Figure A1.8: Calculated and predicted SVI *versus* initial solids concentration for run GA2.

A1.4 WAHLBERG RUN VT1

Table A1.7: Raw interface height *versus* time data for run VT1.

Time	Height (cm)					
(min)	X_0 = 1.9 (g/L)	X_0 = 3.0 (g/L)	X_0 = 3.7 (g/L)	X_0 = 4.2 (g/L)	X_0 = 6.3 (g/L)	X_0 = 8.4 (g/L)
0.0	173.0	173.0	173.0	173.0	173.0	173.0
7.5	123.0	119.8	125.5	171.6	173.0	173.0
9.0	104.0	105.5	116.0	168.8	172.4	172.5
10.0	93.2	97.2	109.9	166.5	171.9	172.3
11.0	84.5	88.7	104.5	163.8	171.8	172.0
12.0	74.0	80.8	99.5	161.5	171.8	171.7
13.0	66.7	75.8	96.6	159.2	171.7	171.7
14.0	61.0	70.9	93.8	157.3	171.6	171.4
15.0	56.3	67.0	91.0	155.0	171.5	171.2
16.0	53.5	63.8	88.5	152.5	171.2	171.1
17.0	51.4	61.3	86.0	150.6	171.1	170.9
18.0	49.5	59.0	83.8	148.5	170.9	170.7
19.0	47.8	57.0	81.6	146.2	170.8	170.5
20.0	46.0	55.0	79.5	144.0	170.6	170.3
21.0	44.7	53.4	77.5	141.7	170.4	170.0
23.5	41.5	49.5	73.0	136.5	170.0	169.6
25.0	39.9	47.8	70.7	133.5	169.7	169.2
27.5	37.3	44.9	67.3	128.0	169.2	168.6
30.0	35.3	42.8	64.2	123.0	168.7	168.1

Note: Shaded areas represent data used to determine interface settling velocity.

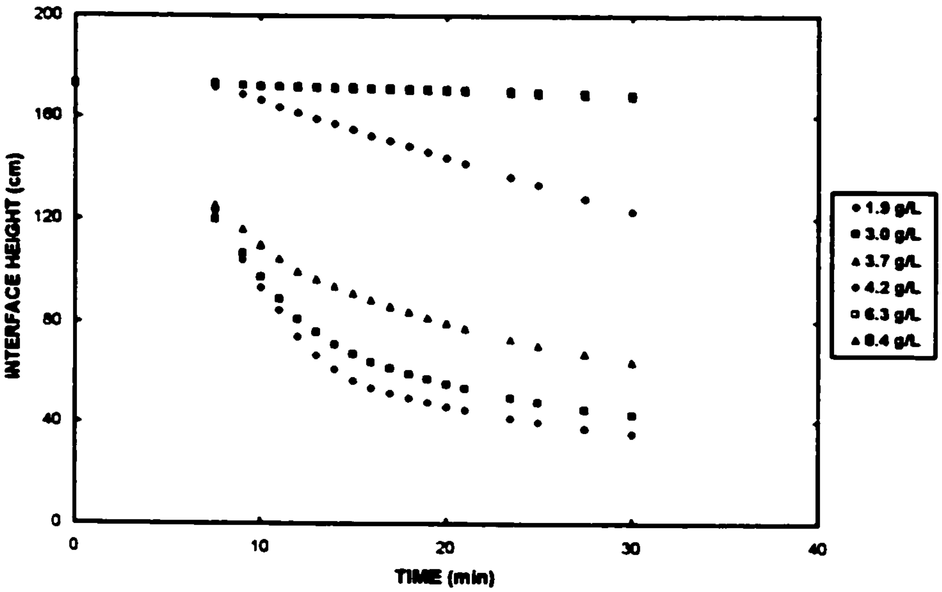

Figure A1.9: Interface height *versus* time for run VT1.

Table A1.8: Interface settling velocity data for run VT1.

X_0 (g/L)	V_S (m/h)	ln V_S
1.9	6.45	1.86
3.0	5.23	1.65
3.7	3.62	1.29
4.2	1.33	0.29
6.3	0.11	-2.23
8.4	0.13	-2.08

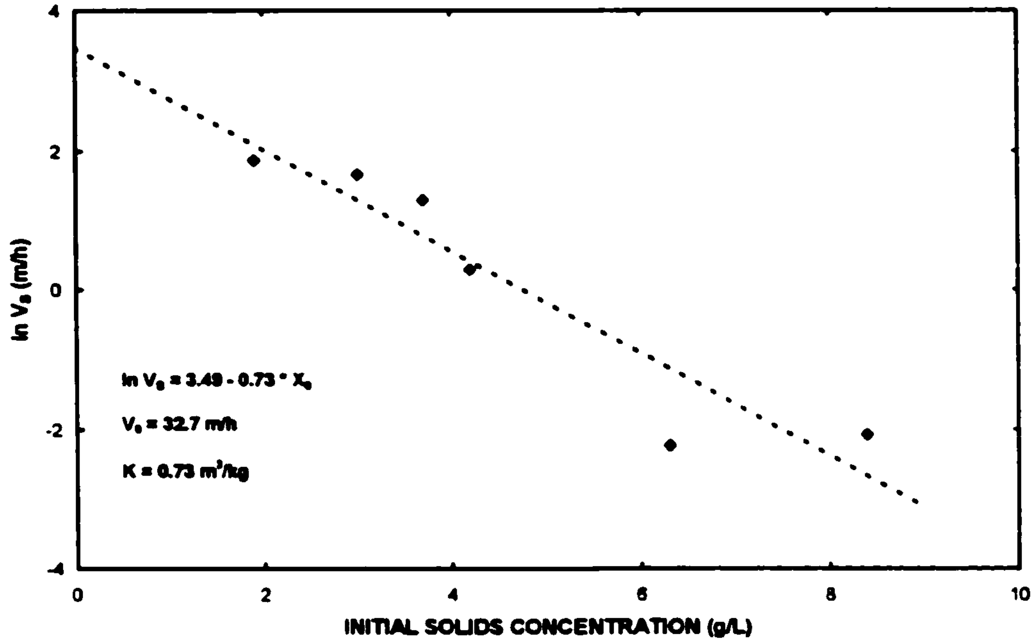

Figure A1.10: Interface settling velocity *versus* initial solids concentration for run VT1.

Table A1.9: Thirty minute and estimated final settled height data for run VT1.

X_0 (g/L)	H_{30} (cm)	H' (cm)	Final Settled Height Fraction	Calculated SVI (mL/g)
1.9	35.3	32.0	0.18	107
3.0	42.8	40.0	0.23	83
3.7	64.2	61.0	0.35	100
4.2	123.0	100.0	0.58	169
6.3	168.7	150.0	0.87	155
8.4	168.1	166.0	0.96	116

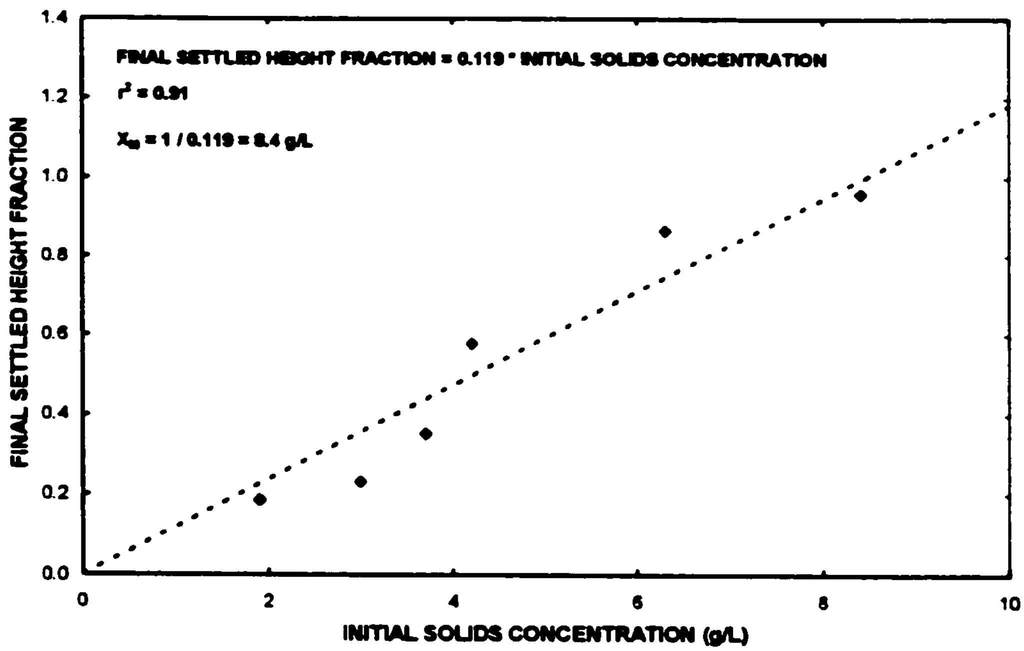

Figure A1.11: Estimated final settled height *versus* initial solids concentration for run VT1.

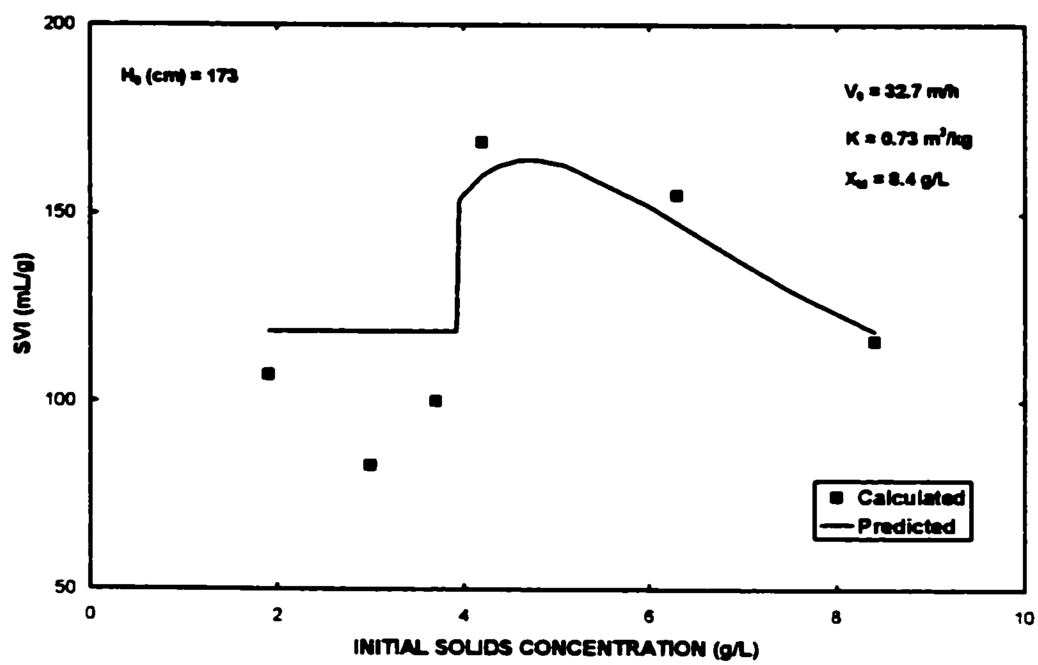

Figure A1.12: Calculated and predicted SVI *versus* initial solids concentration for run VT1.

A1.5 BYE RUN 06/04/97

Table A1.10: Raw interface height *versus* time data for run 06/04/97.

X_0 = 1.4 g/L		X_0 = 2.4 g/L		X_0 = 3.9 g/L		X_0 = 5.2 g/L		X_0 = 6.5 g/L	
Time (min)	Height (cm)	Time (min)	Height (cm)	Time (min)	Height (cm)	Time (min)	Height (cm)	Time (min)	Height (cm)
0.00	50.0	0.00	50.0	0.00	50.0	0.00	50.0	0.00	50.0
0.12	49.0	0.20	49.0	0.58	49.0	3.00	49.0	3.25	49.0
0.22	48.0	0.37	48.0	1.33	48.0	5.75	48.0	7.50	48.0
0.33	47.0	0.47	47.0	2.00	47.0	8.42	47.0	11.87	47.0
0.43	46.0	0.60	46.0	2.67	46.0	11.00	46.0	16.58	46.0
0.55	45.0	0.73	45.0	3.33	45.0	13.50	45.0	20.92	45.5
0.67	44.0	0.87	44.0	4.00	44.0	16.00	44.0	25.13	44.0
0.76	43.0	1.00	43.0	4.67	43.0	18.50	43.0	30.00	43.0
0.86	42.0	1.13	42.0	5.33	42.0	[illegible]	42.0	[illegible]	42.0
0.97	41.0	1.25	41.0	6.00	41.0	[illegible]	41.0	[illegible]	41.0
1.05	40.0	1.37	40.0	6.67	40.0	[illegible]	40.0	42.50	40.0
1.13	39.0	[illegible]	39.0	7.50	39.0	[illegible]	39.0	47.00	39.0
1.20	[illegible]	1.62	[illegible]	10.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	37.0	1.77	37.0	11.00	[illegible]	[illegible]	[illegible]	[illegible]	37.0
[illegible]	[illegible]	[illegible]	[illegible]	12.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	35.0	13.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	14.42	32.0	[illegible]	[illegible]	[illegible]	[illegible]
1.67	[illegible]	[illegible]	[illegible]	16.00	31.0	[illegible]	[illegible]	[illegible]	33.0
[illegible]	[illegible]	2.27	32.0	17.25	30.0	[illegible]	32.0	[illegible]	32.0
[illegible]	[illegible]	[illegible]	31.0	18.83	29.0	52.50	31.0	[illegible]	31.0
1.92	30.0	2.53	30.0	20.58	28.0	59.50	29.0	91.17	30.0
2.00	29.0	2.63	29.0	22.58	27.0	63.50	28.0		
2.08	28.0	2.75	28.0	24.75	26.0	67.17	27.0		
2.17	27.0	[illegible]	27.0	27.42	25.0	71.33	26.0		
[illegible]	[illegible]	[illegible]	[illegible]	30.00	24.0	76.00	25.0		
2.33	25.0	3.27	25.0	33.25	23.0				
2.42	24.0	3.52	24.0	36.50	22.0				
2.50	23.0	3.83	23.0	40.00	21.0				
2.58	22.0	4.25	22.0	44.00	20.0				
2.67	21.0	4.70	21.0	60.00	17.0				
2.75	20.0	5.25	20.0	67.67	16.0				
2.83	19.0	6.08	19.0	74.75	15.0				
2.92	18.0	9.97	16.0						
3.00	17.0	11.72	15.0						
3.08	16.0	14.13	14.0						
3.17	15.0	17.33	13.0						
3.25	14.0	21.33	12.0						
3.67	13.0	27.00	11.0						
4.50	12.0	30.00	10.5						
5.50	11.0	43.00	9.0						
7.25	10.0								

9.00	9.0
16.25	7.0
24.00	6.0
30.00	5.5
37.00	5.0

Note: Shaded areas represent data used to determine interface settling velocity.

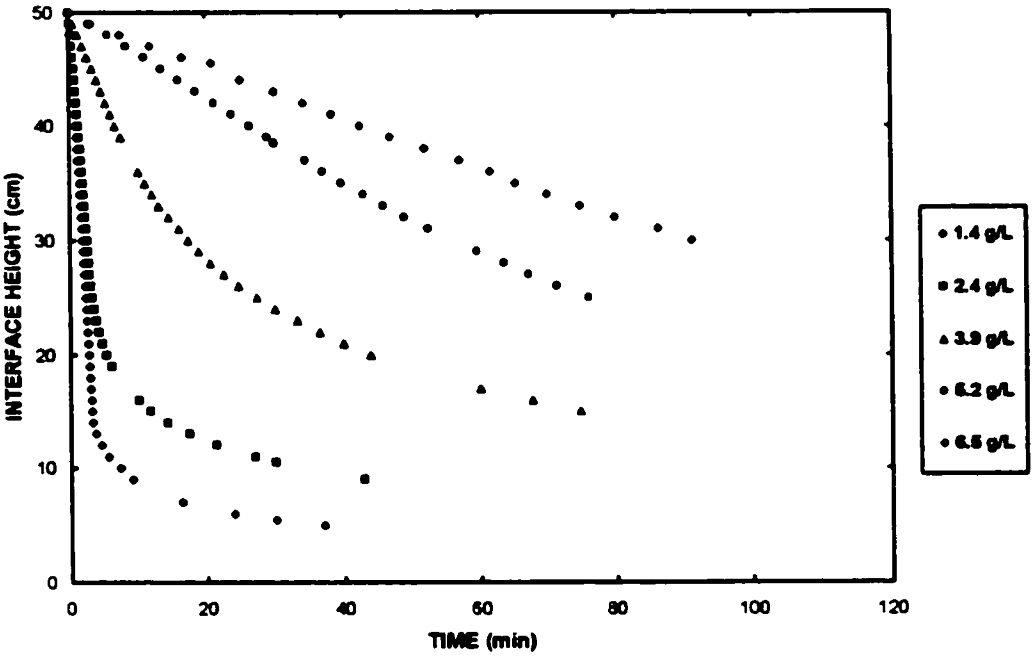

Figure A1.13: Interface height *versus* time for run 06/04/97.

Table A1.11: Interface settling velocity data for run 06/04/97.

X_0 (g/L)	V_S (m/h)	ln V_S
1.4	6.78	1.91
2.4	4.90	1.59
3.9	0.73	-0.32
5.2	0.22	-1.49
6.5	0.13	-2.02

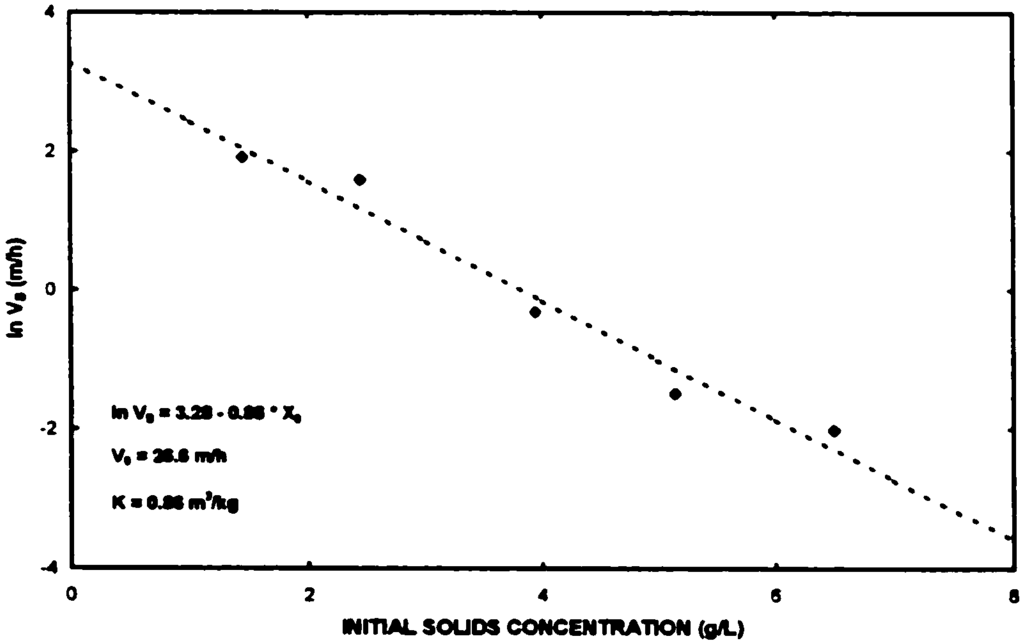

Figure A1.14: Interface settling velocity *versus* initial solids concentration for run 06/04/97.

Table A1.12: Thirty minute and estimated final settled height data for run 06/04/97.

X_0 (g/L)	H_{30} (cm)	H' (cm)	Final Settled Height Fraction	Calculated SVI (mL/g)
1.4	5.5	5.0	0.10	79
2.4	10.5	9.0	0.17	88
3.9	24.0	15.0	0.29	123
5.2	38.5	25.0	0.48	148
6.5	43.0	30.0	0.60	132
7.8	45.0	-	-	115
8.9	46.5	-	-	104

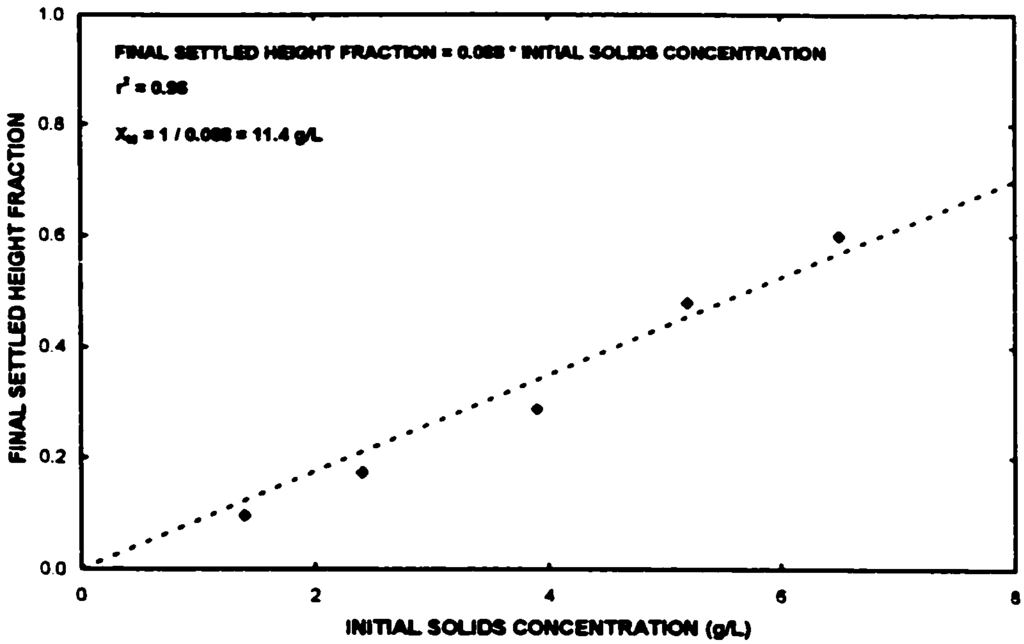

Figure A1.15: Estimated final settled height *versus* initial solids concentration for run 06/04/97.

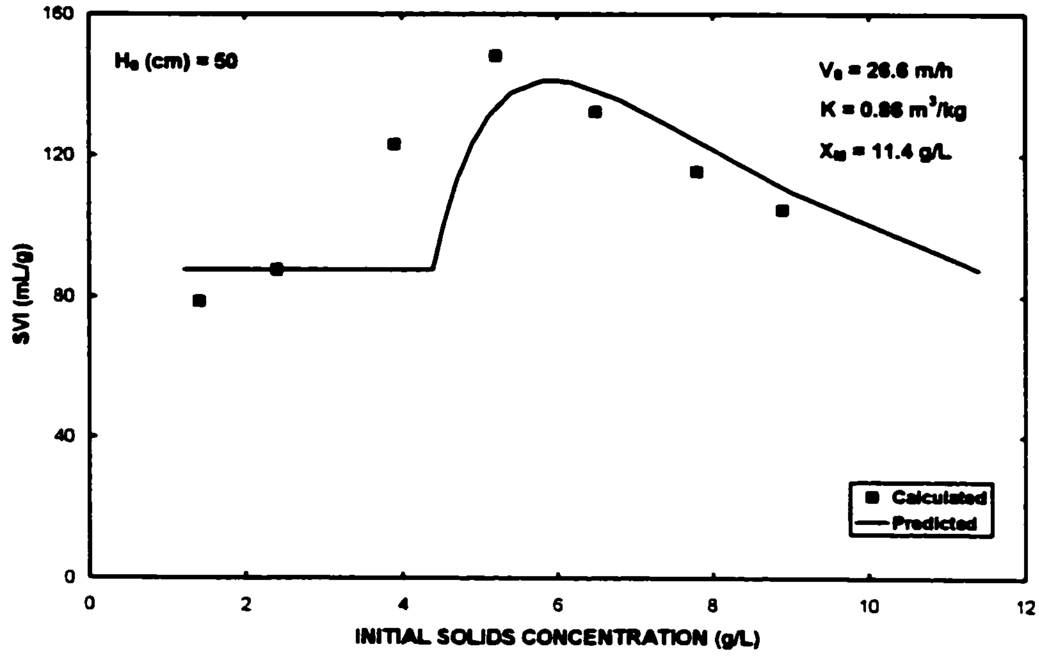

Figure A1.16: Calculated and predicted SVI *versus* initial solids concentration for run 06/04/97.

A1.6 BYE RUN 06/11/97

Table A1.13: Raw interface height *versus* time data for run 06/11/97.

X_0 = 1.9 g/L		X_0 = 3.3 g/L		X_0 = 4.8 g/L		X_0 = 6.2 g/L		X_0 = 7.5 g/L	
Time (min)	Height (cm)	Time (min)	Height (cm)	Time (min)	Height (cm)	Time (min)	Height (cm)	Time (min)	Height (cm)
0.00	50.0	0.00	50.0	0.00	50.0	0.00	50.0	0.00	50.0
0.27	48.0	0.25	49.0	0.92	49.0	3.08	49.0	5.05	49.0
0.48	46.0	0.42	48.0	1.85	48.0	6.25	48.0	10.33	48.0
0.70	44.0	0.58	47.0	3.00	47.0	9.25	47.0	15.50	47.0
0.88	42.0	0.77	46.0	4.17	46.0	12.41	46.0	20.75	46.0
1.07	40.0	0.92	45.0	5.28	45.0	[illegible]	[illegible]	26.00	45.0
1.22	[illegible]	1.08	44.0	6.58	44.0	[illegible]	44.0	29.00	44.5
1.40	[illegible]	1.27	43.0	7.97	43.0	[illegible]	43.0	[illegible]	43.0
1.57	[illegible]	[illegible]	42.0	[illegible]	42.0	[illegible]	42.0	[illegible]	42.0
1.75	[illegible]	[illegible]	41.0	10.92	41.0	[illegible]	41.0	[illegible]	41.0
1.90	[illegible]	1.70	40.0	12.33	40.0	[illegible]	40.0	[illegible]	40.0
2.10	[illegible]	[illegible]	39.0	13.92	39.0	[illegible]	39.0	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	38.0	15.67	[illegible]	[illegible]	38.0	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	37.0	17.25	37.0	[illegible]	37.0	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	36.0	19.00	36.0	[illegible]	36.0	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	35.0	20.75	35.0	[illegible]	34.0	[illegible]	[illegible]
3.02	19.0	[illegible]	34.0	22.83	34.0	[illegible]	[illegible]	[illegible]	33.0
3.25	18.0	3.00	33.0	[illegible]	33.0	[illegible]	32.0	[illegible]	32.0
3.52	17.0	3.17	32.0	26.83	32.0	66.58	31.0		
3.92	16.0	[illegible]	31.0	28.92	31.0	70.83	30.0		
4.50	15.0	3.67	30.0	31.17	30.0	74.83	29.0		
5.12	14.0	4.00	29.0	33.58	29.0	80.58	28.0		
6.42	13.0	4.37	28.0	36.50	28.0	84.83	27.0		
7.67	12.0	4.75	27.0	39.00	27.0	90.33	26.0		
9.75	11.0	5.35	26.0	42.17	26.0	103.33	24.0		
12.08	10.0	6.00	25.0	45.25	25.0	109.83	23.0		
20.25	8.0	6.85	24.0	49.00	24.0				
28.00	7.0	7.85	23.0	53.50	23.0				
42.00	6.0	9.08	22.0	56.75	22.0				
		10.58	21.0	61.50	21.0				
		12.25	20.0	65.52	20.0				
		14.75	19.0	71.00	19.0				
		23.00	16.0	78.08	18.0				
		28.00	15.0						
		30.00	14.5						
		38.50	13.0						
		46.00	12.0						
		56.00	11.0						

Note: Shaded areas represent data used to determine interface settling velocity.

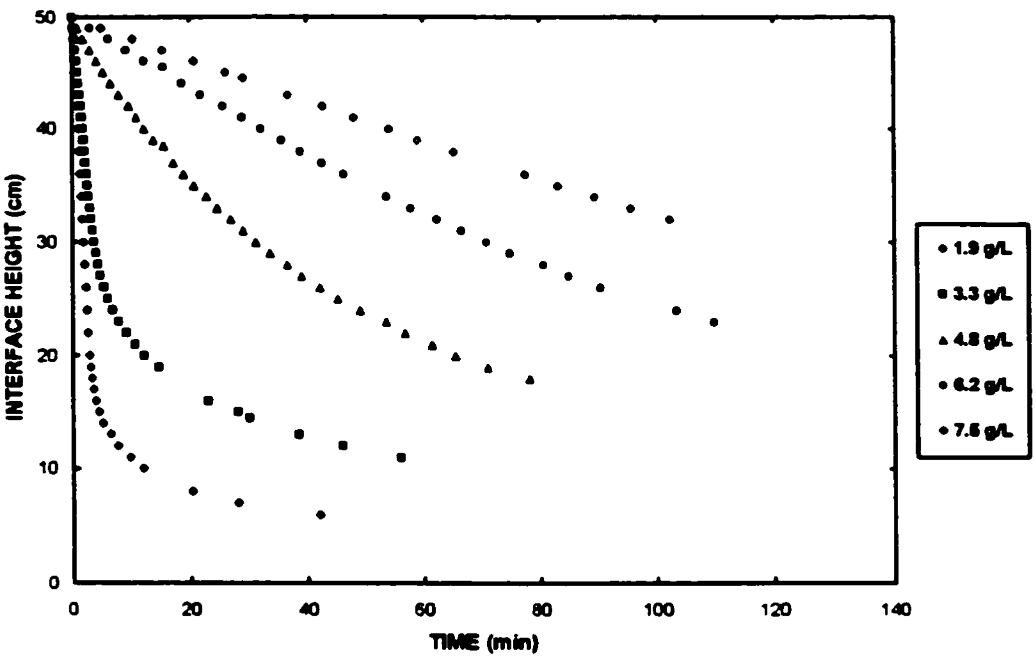

Figure A1.17: Interface height *versus* time for run 06/11/97.

Table A1.14: Interface settling velocity data for run 06/11/97.

X_0 (g/L)	V_S (m/h)	ln V_S
1.9	6.57	1.88
3.3	3.25	1.18
4.8	0.41	-0.90
6.2	0.18	-1.74
7.5	0.11	-2.24

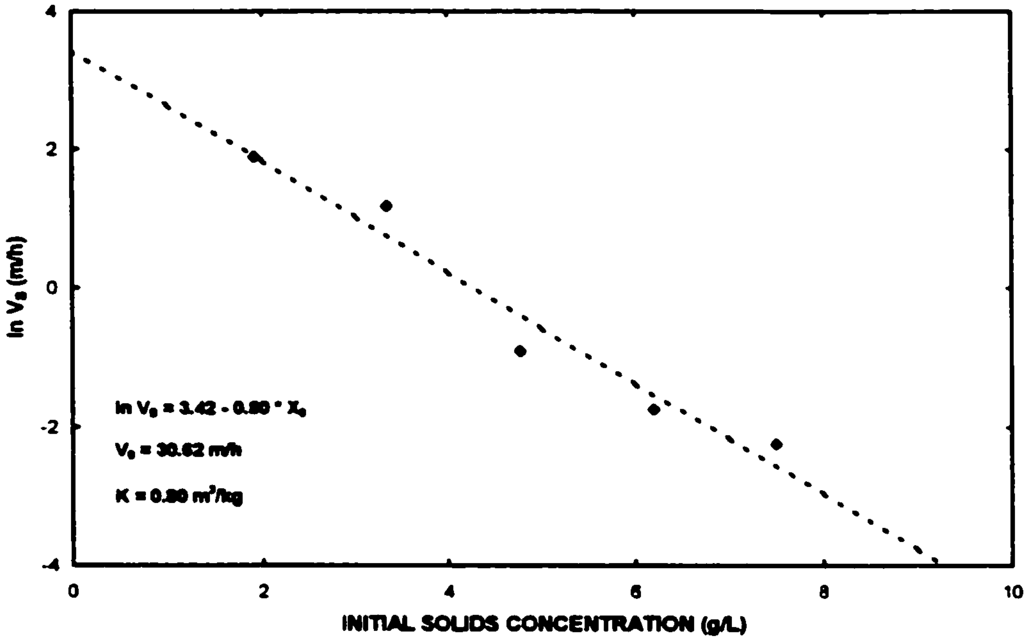

Figure A1.18: Interface settling velocity *versus* initial solids concentration for run 06/11/97.

Table A1.15: Thirty minute and estimated final settled height data for run 06/11/97.

X_0 (g/L)	H_{30} (cm)	H' (cm)	Final Settled Height Fraction	Calculated SVI (mL/g)
1.9	7.0	6.0	0.12	74
3.3	14.5	11.0	0.21	88
4.8	30.0	18.0	0.35	125
6.2	41.0	23.0	0.44	132
7.5	44.5	32.0	0.63	119
9.0	46.0	-	-	102
10.0	47.0	-	-	94
11.8	48.0	-	-	81

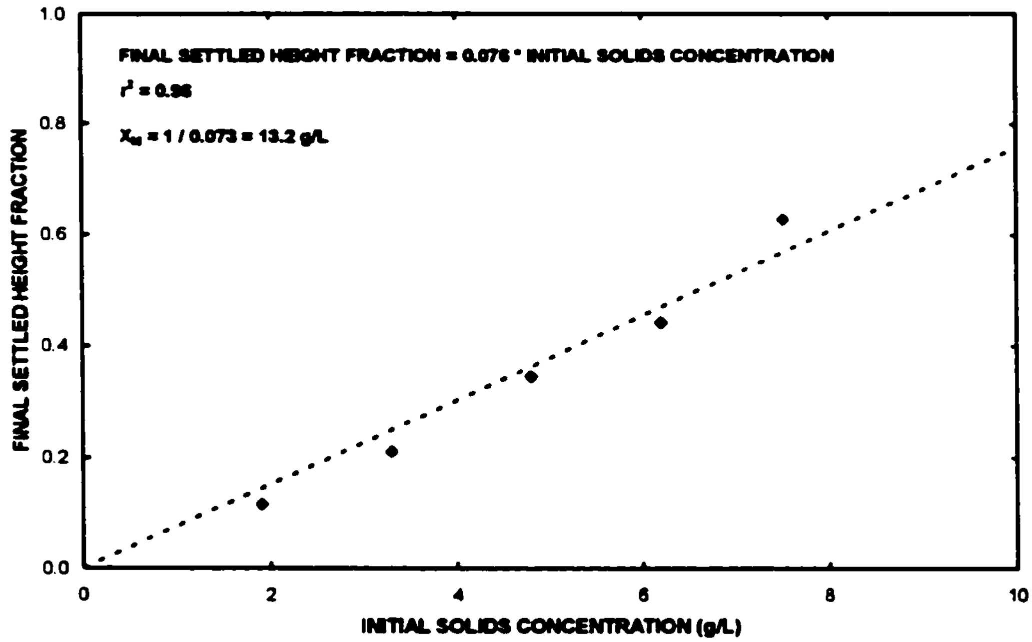

Figure A1.19: Estimated final settled height *versus* initial solids concentration for run 06/11/97.

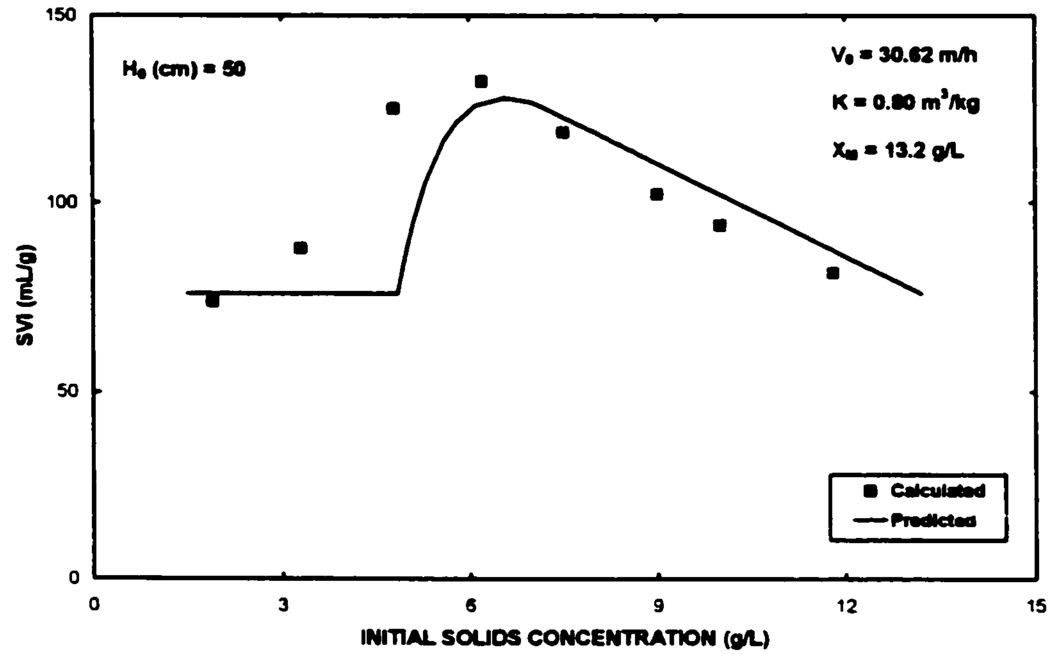

Figure A1.20: Calculated and predicted SVI *versus* initial solids concentration for run 06/11/97.

APPENDIX TWO

EXPLANATION OF FLUX THEORY DESIGN AND OPERATION CHART

A2.1 INTRODUCTION

The purpose of this Appendix is to provide a detailed explanation of the IAWQ design and operation chart (Ekama *et al.*, 1997) used in Chapter 4 of this thesis. An example of the diagram is shown in Figure A2.1 below.

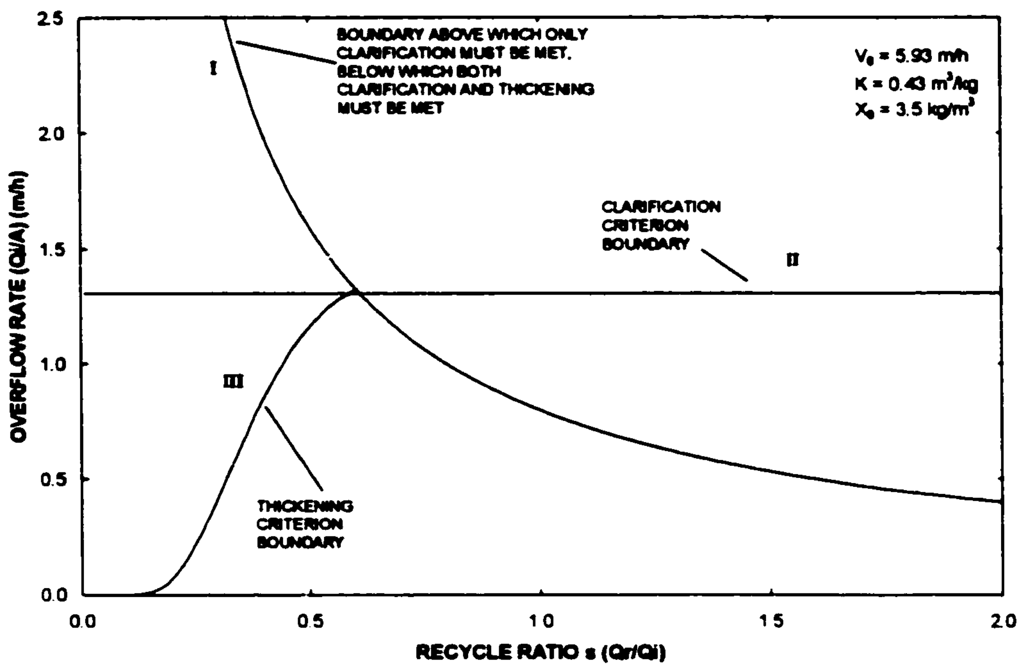

Figure A2.1: Flux theory design and operation chart.

The design and operation chart consists of three lines (labelled I, II, and III in Figure A2.1). Derivation of these lines is demonstrated later in this Appendix. Lines II and III represent safety envelopes for clarification and thickening criteria, respectively. Points falling above these lines correspond to overloaded failure conditions with respect to the settler thickening and/or clarification function. Line I defines the boundary between operating conditions where both the clarification and thickening functions govern settling tank operation (region below Line I), or the clarification criterion only governs (region above Line I). Essentially the design and operation chart is an alternative representation of the more familiar state point diagram shown in Figure A2.2 below.

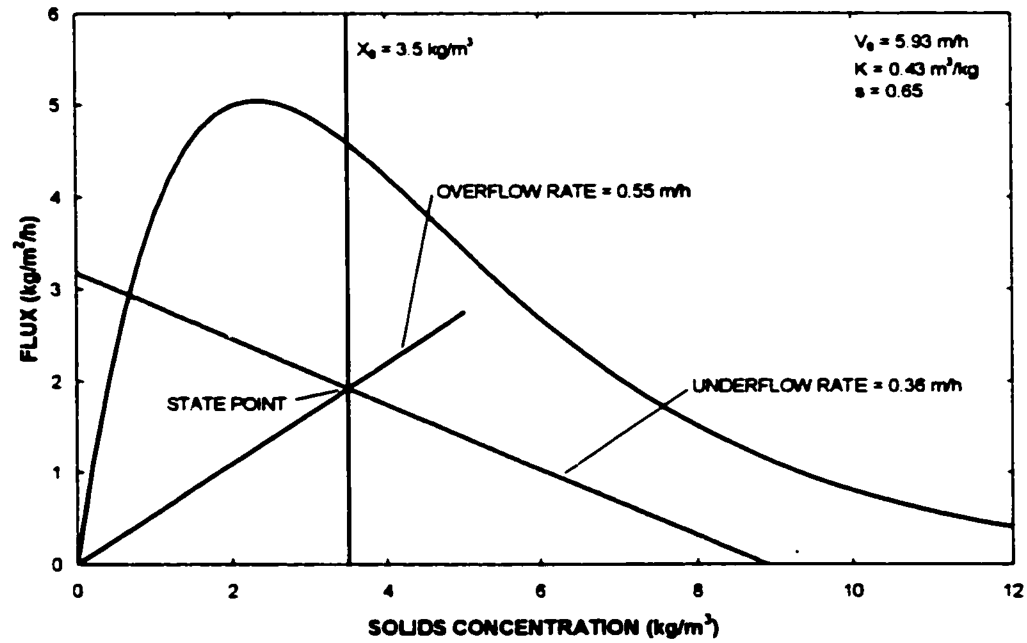

Figure A2.2: State point flux theory diagram.

The state point diagram consists of a settling flux curve with three lines representing the solids loading rate condition superimposed on it:

1. The overflow rate operating line (with slope Qi/A);
2. The underflow rate operating line (with slope -QR/A); and
3. The operating solids concentration.

These lines essentially represent a steady state solids mass balance around the settling tank. The "state point" is defined as the intersection of the overflow rate and operating solids concentration lines. The underflow rate line passes through the state point and intersects the horizontal axis at the underflow concentration (i.e. the return activated sludge concentration). An underloaded, critically loaded, or overloaded settling tank can be identified in state point analysis by the position of the state point and the underflow rate operating line relative to the descending limb of the settling flux curve:

1. If the state point is below the settling flux curve and

    a. if the underflow rate operating line falls **below** the descending limb of the settling flux curve, the settling tank is **underloaded**. [The settling tank is able to satisfy both the thickening and clarification functions];

    b. if the underflow rate operating line is **tangential** to the descending limb of the settling flux curve, the settling tank is **critically loaded**. [The settling tank is able to satisfy the clarification function, but loading conditions are critical regarding the thickening function];

    c. if the underflow rate operating line passes **above** the descending limb of the settling flux curve, the settling tank is **overloaded**. [The settling tank is able to satisfy the clarification function, but is overloaded with respect to the thickening function].

2. If the state point lies on the settling flux curve and

    a. if the underflow rate operating line falls below the descending limb of the settling flux curve, the settling tank is critically loaded. [The settling tank is able to satisfy the thickening function, but loading conditions are critical with respect to the clarification function];

    b. if the underflow rate operating line passes above the descending limb of the settling flux curve, the settling tank is overloaded. [The settling tank is critically loaded with respect to the clarification function, but is overloaded with respect to the thickening function].

3. If the state point is above the settling flux curve the settling tank is overloaded. [The settling tank is overloaded with respect to the clarification function and solids entering the settling tank will be carried upwards and over the effluent weirs].

Figure A2.2 is an example of a state point diagram for an underloaded settling tank corresponding to condition (1a) above.

The state point diagram is useful for interpreting the IAWQ design and operation chart. In Figure A2.3 shown below, state point diagrams for various settler loading conditions are shown. The corresponding operating point for each loading condition also is shown on the IAWQ design and operation chart.

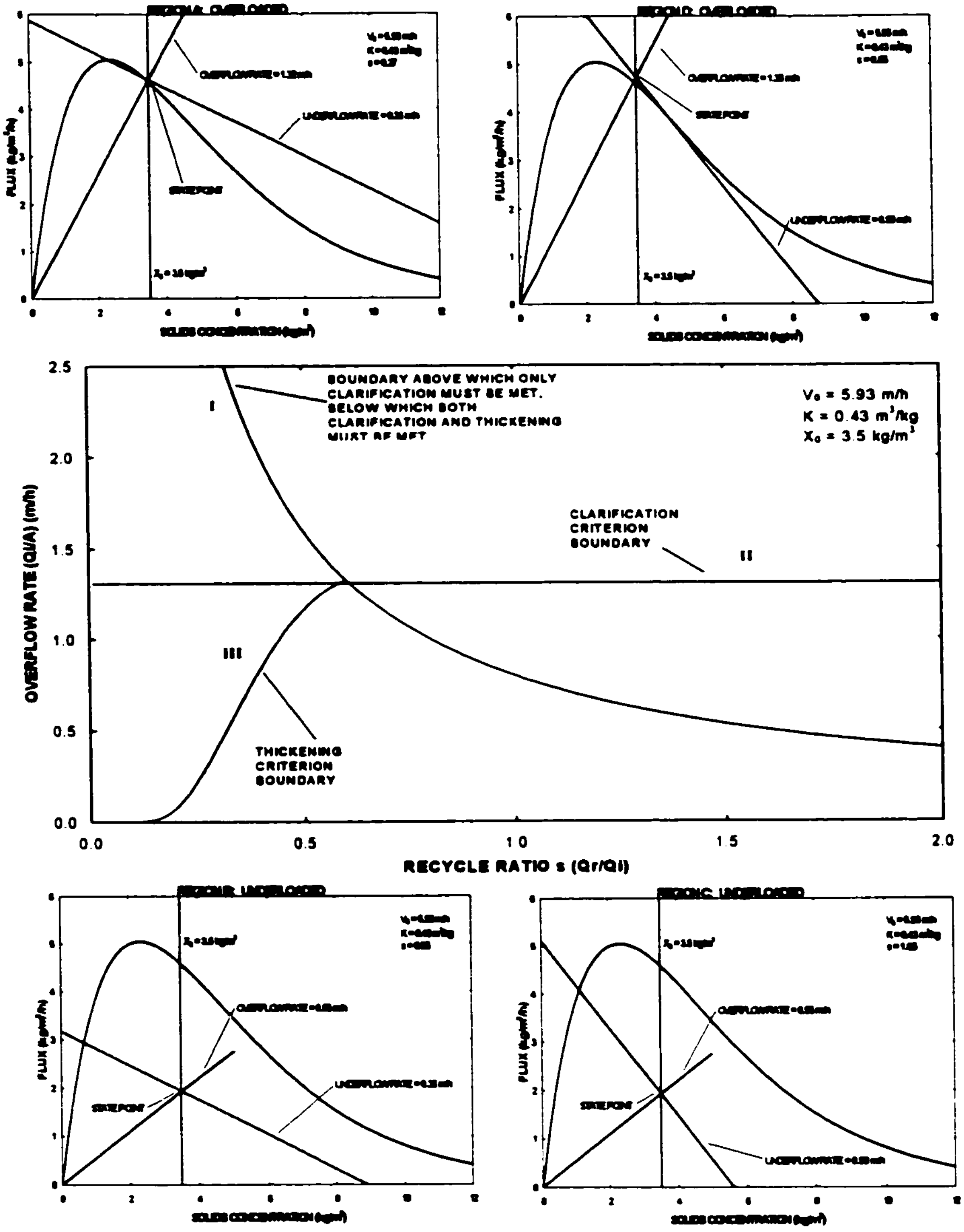

Figure A2.3: State point flux theory diagrams for points A, B, C, and D in the IAWQ design and operation chart.

A2.2 DERIVATION OF LINES I, II, AND III FOR DESIGN AND OPERATION CHART

A.2.1 Line I

The design and operation chart results from a mathematical examination of the settling flux curve used for state point analysis. Recall from condition (1b) above that the settling tank is critically loaded when the underflow rate operating line is tangential to the descending limb of the settling flux curve and the state point lies below the settling flux curve. This condition is shown in Figure A2.4.

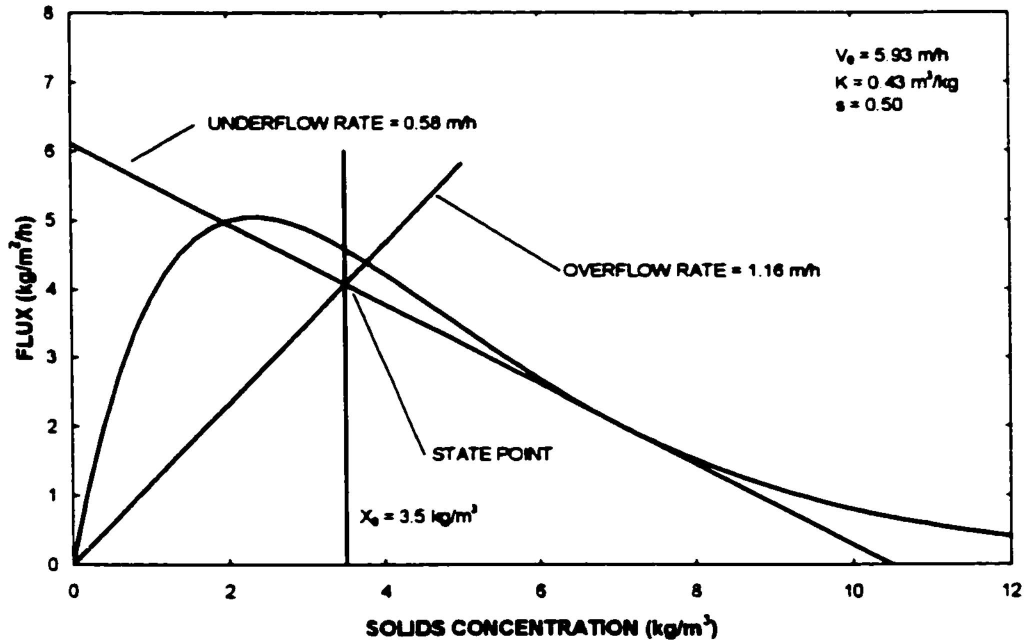

Figure A2.4: State point diagram for critically loaded settling tank.

A mathematical analysis leads to an equation for the tangent to the settling flux curve. The equation of the settling flux curve is given by the product of solids concentration and sludge settling velocity:

$$G(X) = X \cdot V_0 \, e^{-KX} \tag{A2.1}$$

where G(X) = settling flux;

X = solids concentration;

V_0, K = Vesilind settling parameters

The first derivative of Eq. A2.1 yields the slope of tangents to the settling flux as a function of solids concentration:

$$\begin{aligned}\frac{\partial G(X)}{\partial X} &= V_0\, e^{-KX} + X\left(-K \cdot V_0\, e^{-KX}\right) \\ &= V_0\, e^{-KX} - K \cdot X \cdot V_0\, e^{-KX} \\ &= V_0\, e^{-KX}\,(1 - K \cdot X)\end{aligned} \qquad \text{(A2.2)}$$

The maximum underflow rate where a tangent to the settling flux curve still is possible (i.e. the maximum, or "steepest" tangent) occurs at the inflection point of the settling flux curve. The corresponding solids concentration at the inflection point is obtained by setting the second derivative to zero:

$$\begin{aligned}\frac{\partial^2 G(X)}{\partial X^2} &= -K \cdot V_0\, e^{-KX}\,(1 - K \cdot X) - K \cdot V_0\, e^{-KX} \\ &= -K \cdot V_0\, e^{-KX}\,[(1 - K \cdot X) + 1] \\ &= -K \cdot V_0\, e^{-KX}\,(2 - K \cdot X)\end{aligned}$$

$$\text{So, } \frac{\partial^2 G(X)}{\partial X^2} = 0 \text{ when } X = \frac{2}{K} \qquad \text{(A2.3)}$$

The slope of the tangent at the inflection point is given by substituting the solution of Eq. A2.3 (i.e. $X = 2 / K$) into Eq, A2.2. This yields the critical underflow rate – for underflow rates above this critical value, a tangent to the settling flux curve is not possible.

$$\begin{aligned}\frac{\partial G}{\partial X}\left(X = \frac{2}{K}\right) &= V_0\, e^{-K\left(\frac{2}{K}\right)}\left(1 - K \cdot \frac{2}{K}\right) \\ &= -\frac{V_0}{e^2}\end{aligned}$$

$$\therefore \left(\frac{Q_R}{A}\right)_{CRIT} = \frac{V_0}{e^2} \qquad \text{(A2.4)}$$

where Q_R = underflow rate;

A = settling tank area;

State point conditions 1 through 3 listed above stipulate that when the slope of the underflow rate operating line is too steep to make a tangent to the settling flux curve [i.e. $Q_R/A > (Q_R/A)_{CRIT}$], the settling tank loading conditions must be such that the state point falls below the settling flux curve (i.e. the clarification function governs).

If the underflow rate is less than the critical value [i.e. $Q_R/A < (Q_R/A)_{CRIT}$], it is possible for the underflow rate operating line to be tangential to the settling flux curve. For this situation, the settling tank loading conditions must be such that the state point falls below the settling flux curve **and** the underflow rate operating line falls below the descending limb of the settling flux curve (i.e. both thickening and clarification may govern).

Line I on the design and operation chart is given by the equation for the critical underflow rate written in terms of the overflow rate, with the recycle ratio s defined as Q_R/Q_i:

$$\text{If } s = \frac{Q_R}{Q_i}, \frac{Q_R}{A} \text{ becomes}$$

$$\frac{Q_R}{A} = \frac{s \cdot Q_i}{A} = \frac{V_0}{e^2}$$

$$\therefore \frac{Q_i}{A} = \frac{V_0}{e^2 \cdot s} \qquad \text{(A2.5)}$$

where Q_i = influent flow rate;

s = underflow recycle ratio;

A = settling tank area;

Figure A2.5 below shows the design and operating chart with only Line I which plots the critical underflow rate in terms of the overflow rate and recycle ratio.

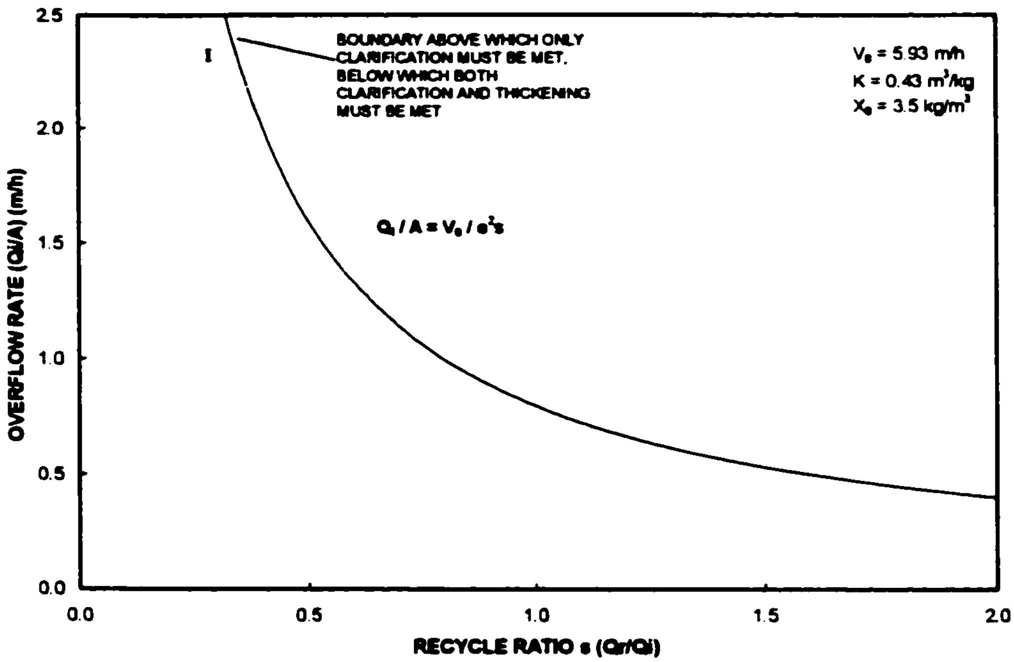

Figure A2.5: Design and operating chart with only Line I shown.

A.2.2 Line II

State point condition 3 listed above requires that for a given settling tank feed solids concentration (i.e. X_0), the settling tank overflow rate cannot be greater than the solids settling velocity at that concentration. That is;

$$\frac{Q_i}{A} \leq V_0\, e^{-KX_0} \tag{A2.6}$$

where X_0 = settling tank feed concentration;

On the design and operating chart, this condition is represented by a constant line (Line II) that is independent of underflow recycle ratio. The design and operating chart with only Lines I and II drawn is shown in Figure A2.6 below.

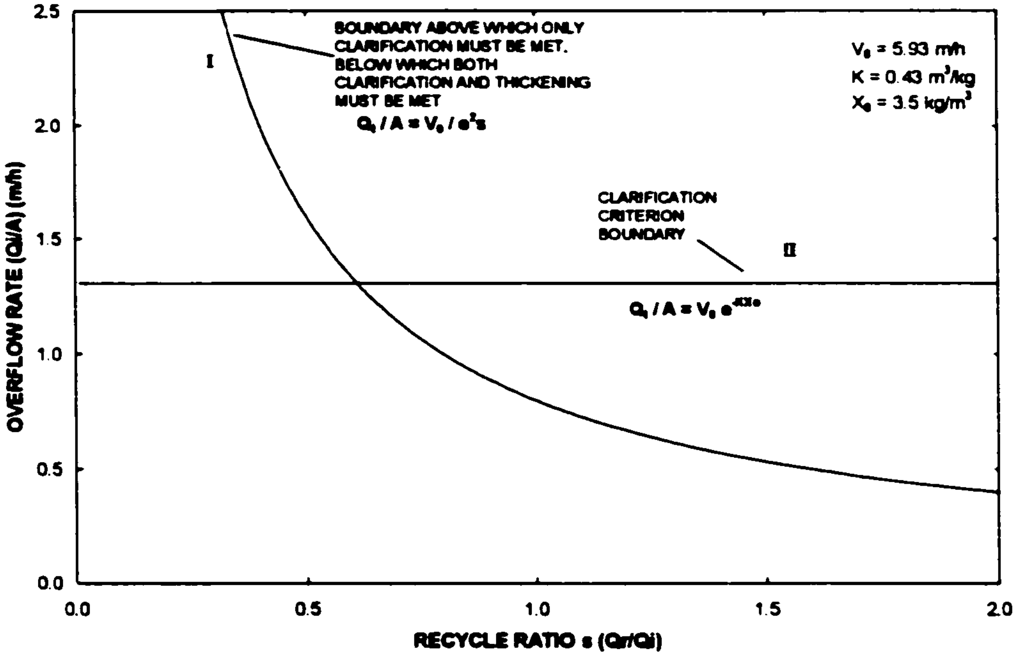

Figure A2.6: Design and operating chart with only Lines I& II shown.

A.2.3 Line III

On the state point diagram, the intercept of the underflow rate operating line with the vertical flux axis yields the settling tank applied flux. Recall from state point condition 1b listed above that when the underflow rate operating line is tangential to the settling flux curve, the settling tank is critically loaded. Therefore, for a critically loaded settling tank, the applied flux is equal to the limiting flux. This is shown graphically in Figure A2.7 below.

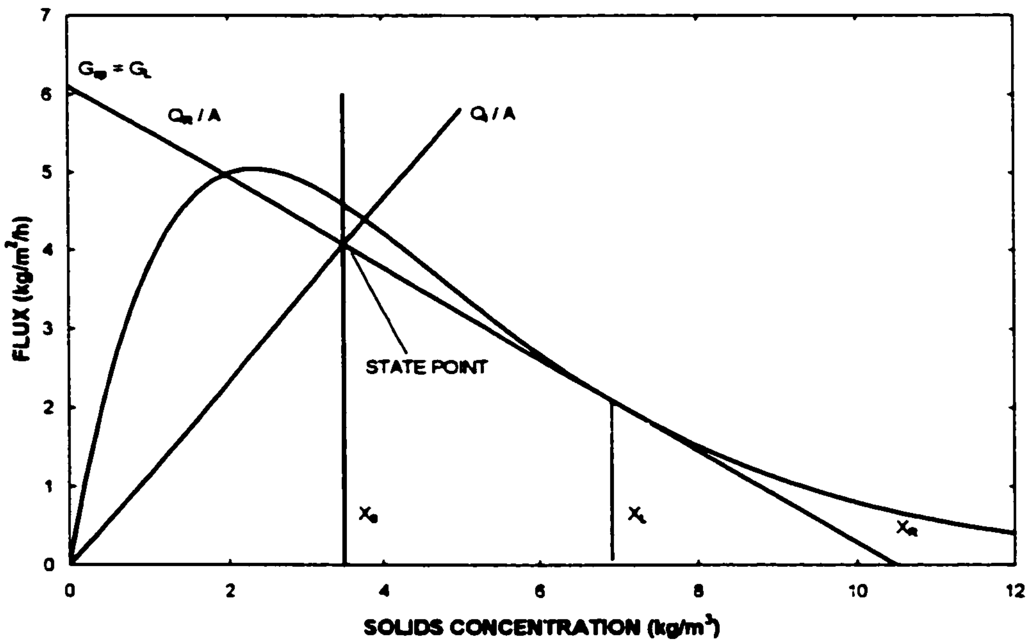

Figure A2.7: State point diagram for a critically loaded settling tank.

The settling tank applied flux is given by:

$$G_{ap} = \left(\frac{Q_i + Q_R}{A} \right) \cdot X_0 \qquad \text{(A2.7)}$$

where G_{ap} = settling tank applied flux;

Q_i = influent flow rate;

Q_R = underflow rate;

A = settling tank area;

So under critical loading conditions:

$$G_{ap} = \left(\frac{Q_i + Q_R}{A}\right) \cdot X_0 = G_L$$
$$\therefore \frac{Q_i}{A} + s \cdot \frac{Q_i}{A} = \frac{G_L}{X_0}$$
$$\therefore \frac{Q_i}{A} = \frac{G_L}{X_0 \cdot (1 + s)} \qquad \text{(A2.8)}$$

where G_L = settling tank limiting flux;

s = underflow recycle ratio;

The equation of the tangent line in Figure A2.7 is given by:

$$G(X) = G_L \cdot \left(1 - \frac{X}{X_R}\right) \qquad \text{(A2.9)}$$

where X = solids concentration;

X_R = underflow recycle solids concentration;

The equation of the settling flux curve is given by the product of solids concentration and sludge settling velocity (Eq. A2.1). At the point of tangency (i.e. $X = X_L$ in Figure A2.7) Eqs. A2.1 and A2.9 are equal:

$$G_L \cdot \left(1 - \frac{X_L}{X_R}\right) = X_L \cdot V_0\, e^{-KX_L} \qquad \text{(A2.10)}$$

Visual inspection of Figure A2.7 indicates that the slope of the tangent line is given by the ratio of G_L to X_R. Recall that the slope of the tangent also is given by the first derivative (i.e. Eq. A2.2) evaluated at the point of tangency (i.e. $X = X_L$):

$$V_0\, e^{-KX_L} \cdot (1 - K \cdot X_L) = -\frac{G_L}{X_R}$$
$$\therefore G_L = -X_R \cdot V_0\, e^{-KX_L} \cdot (1 - K \cdot X_L) \qquad \text{(A2.11)}$$

Now, Eq. A2.11 for G_L may be substituted into Eq. A2.10:

$$-X_R \cdot V_0 e^{-KX_L} \cdot (1 - K \cdot X_L) \cdot \left(1 - \frac{X_L}{X_R}\right) = X_L \cdot V_0 e^{-KX_L}$$

$$\therefore -X_R \cdot \left(1 - \frac{X_L}{X_R} - K \cdot X_L + \frac{K \cdot X_L^{\,2}}{X_R}\right) = X_L$$

$$\therefore K \cdot X_L^{\,2} - K \cdot X_L \cdot X_R + X_R = 0 \qquad \text{(A2.12)}$$

Solving Eq. A2.12 for X_L (using the quadratic formula and ignoring the negative root) gives:

$$X_L = \frac{K \cdot X_R + \sqrt{K^2 \cdot X_R^{\,2} - 4 \cdot K \cdot X_R}}{2 \cdot K}$$

$$= \frac{K \cdot X_R}{2 \cdot K} + \frac{\sqrt{K^2 \cdot X_R^{\,2} \cdot \left(1 - \frac{4}{K \cdot X_R}\right)}}{2 \cdot K}$$

$$= \frac{X_R}{2} + \frac{X_R}{2} \cdot \sqrt{1 - \frac{4}{K \cdot X_R}}$$

$$= \frac{X_R}{2} \cdot \left(1 + \sqrt{1 - \frac{4}{K \cdot X_R}}\right) \qquad \text{(A2.13)}$$

The underflow recycle solids concentration is related to the settling tank feed solids concentration via a mass balance around the settler:

$$(Q_i + Q_R) \cdot X_0 = Q_R \cdot X_R$$

$$\therefore X_R = \left(1 + \frac{1}{s}\right) \cdot X_0$$

$$\therefore X_R = \frac{(1 + s) \cdot X_0}{s} \qquad \text{(A2.14)}$$

Eq. A2.14 may be substituted into Eq. A2.13:

$$X_L = \frac{(1+s)\cdot X_0}{2\cdot s}\cdot\left(1+\sqrt{1-\frac{4\cdot s}{K\cdot(1+s)\cdot X_0}}\right)$$

Let $\alpha = \sqrt{1-\frac{4\cdot s}{K\cdot(1+s)\cdot X_0}}$, then

$$X_L = \frac{(1+s)\cdot X_0}{2\cdot s}\cdot(1+\alpha) \qquad \text{(A2.15)}$$

Substituting Eqs. A2.14 and A2.15 into Eq. A2.11 yields:

$$G_L = \frac{(1+s)\cdot X_0}{s}\cdot V_0\cdot\left\{\frac{K\cdot(1+s)\cdot X_0\cdot(1+\alpha)}{2\cdot s}-1\right\}\exp\left\{\frac{-K\cdot(1+s)\cdot X_0\cdot(1+\alpha)}{2\cdot s}\right\} \qquad \text{(A2.16)}$$

Substituting Eq. A2.16 into Eq. A2.8 and simplifying yields:

$$\frac{Q_i}{A} = \frac{V_0}{s}\cdot\left(\frac{1+\alpha}{1-\alpha}\right)\exp\left\{\frac{-K\cdot(1+s)\cdot X_0\cdot(1+\alpha)}{2\cdot s}\right\} \qquad \text{(A2.17)}$$

Eq. A2.17 yields Line III when plotted on the design and operation chart, shown in its complete form below. Line III represents critical settling tank loading conditions for a given feed concentration and sludge settleability (i.e. tangential underflow rate operating line) for increasing overflow rate and recycle ratio. Moving upwards along Line III shows that it is possible to increase the underflow recycle rate to accommodate increased overflow rates until the critical underflow rate is reached. At that point, the maximum allowable overflow rate is set solely by sludge settleability (i.e. Line II).

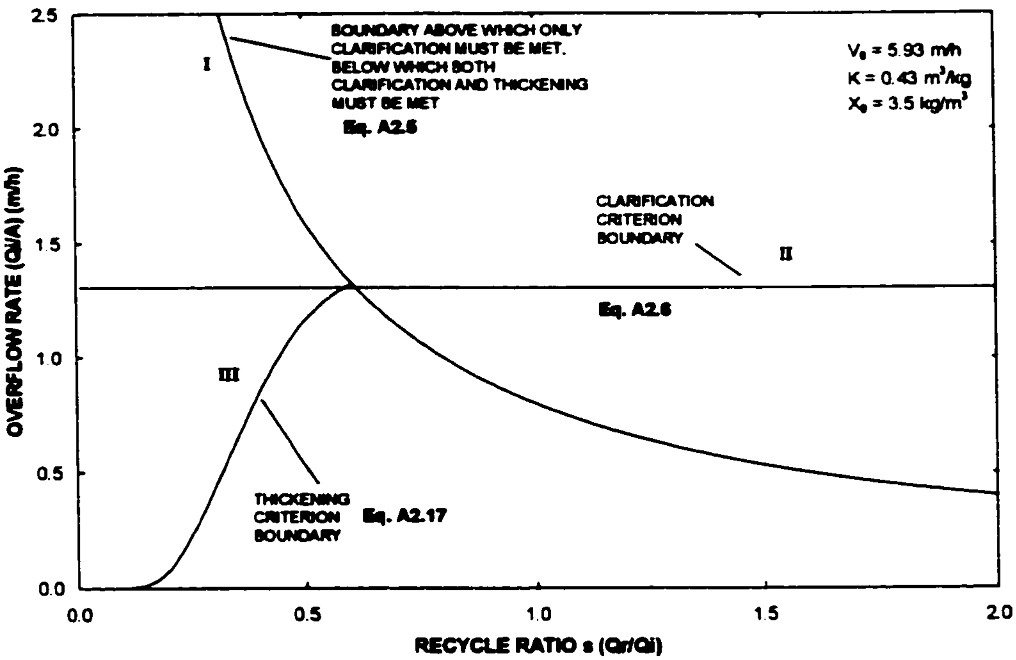

Figure A2.8: Design and operating chart with all lines shown.