

**DEVELOPMENT OF CRITERIA FOR FORMING AND  
MAINTAINING A SLUDGE BLANKET IN AN  
UPFLOW SLUDGE BLANKET CLARIFIER/  
PULSATOR**

I.M.W.K. Illangasinghe

(118068L)

Degree of Doctor of Philosophy

Department of Civil Engineering

University of Moratuwa

Sri Lanka

July 2019

**DEVELOPMENT OF CRITERIA FOR FORMING AND  
MAINTAINING A SLUDGE BLANKET IN AN  
UPFLOW SLUDGE BLANKET CLARIFIER/  
PULSATOR**

I.M.W.K. Illangasinghe

(118068L)

Thesis submitted in partial fulfillment of the requirements for the degree of  
Doctor of Philosophy

Department of Civil Engineering

University of Moratuwa

Sri Lanka

July 2019

## Declaration

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to the University of Moratuwa the non-exclusive right to reproduce and distribute my thesis/dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

I.M.W.K. Illangasinghe

Date:

The above candidate has carried out research for the Ph.D. thesis under our supervision.

Research Supervisors

Professor (Mrs.) Niranjanie Ratnayake

Date: .....

Professor Jagath Manatunge

Date: .....

## **Abstract**

### **Forming and maintaining a sludge (floc) blanket**

**Keywords:** Clarifier, floc blanket, particle structuring, sludge cohesion coefficient, settling velocity

Coagulation and flocculation is attained within a sludge (floc) blanket of an upward flow clarifier unit. In this study cohesivity of the floc blanket, measured by the indicator sludge cohesion coefficient (*SCC*) is used to explain the blanket characteristics and response of the blanket to variations of raw water turbidity (RWT), coagulant dose and ambient conditions.

The study found that *SCC* is an appropriate parameter to monitor floc blanket characteristics. A satisfactory floc blanket is established when *SCC* varies within 0.3 – 1.3 mm/sec and the sludge volume fraction of the blanket is between 0.2 and 0.25. At RWT occurrences > 450 NTU, the blanket cohesivity reduces. Increased coagulant dose leads to restabilization of particles by charge reversal leading to reduction of blanket cohesivity. It is recommended to introduce preliminary sedimentation (prior to clarifier) to effectively treat high turbidity raw water.

Beyond RWT 300 NTU optimum coagulant dose reported from *SCC* test is lower than that of Jar test. This will give savings in coagulants in the range of 6 - 25%. When RWT is > 300 NTU, the linear relationship established using the two parameters during the study can be used to find the optimum dose after carrying Jar test.

The study found that high inflow temperature reduces blanket cohesivity and particle settling efficiency. There is a significant linear relationship between the influent temperature and the effluent quality.

The particle structuring within the blanket is due to hydrodynamic forces between the particles counterbalanced by the cohesive forces. A steady floc blanket is formed when the individual particles are agglomerated and clusters are formed. Cluster formation/destruction is due to the cohesive/inertial forces between particles and/or particle clusters. With low *Re* (< 1) cohesive forces govern. Interstitial spaces between particles vary due to cluster formation/destruction, leading to the increase/decrease of blanket settling velocity.

## **Acknowledgement**

I would like to express my deepest appreciation to all those who provided support enabling me to complete this doctoral thesis.

First, I would like to express my sincere gratitude to my supervisors Professor (Mrs.) Niranjanie Ratnayake, Professor Jagath Manatunge, and progress review chairman Dr. (Mrs.) Niranjalie Jayasuriya for the continuous support during my doctoral studies. Their guidance, motivation and immense knowledge helped me all the time of research, publication, and writing of this thesis.

My sincere thanks also go to Ms. Anuradha Disanayake, Ms. Shasikala Jayathilaka and all other laboratory staff who provided immense support during the laboratory research work. Without their timely support, it would not have been possible to carry out the experiments of this research.

I appreciate the continuing support given by Mr. Asanka Jayasinghe by type setting this document as well as all other documentation work during my study period.

I have to appreciate the guidance given by the Progress Review Committee for their valuable comment and advice, which were invaluable in the advancement of this research.

Furthermore, I would also like to acknowledge the National Water Supply and Drainage Board for allowing me to use of Kandy South Treatment Plant and the laboratory facilities for my research studies.

Last but not the least, I would like to thank my family and friends for supporting me spiritually throughout the study period.

## TABLE OF CONTENT

<b>Declaration</b>	<b>i</b>
<b>Abstract</b>	<b>ii</b>
<b>Acknowledgement</b>	<b>iii</b>
<b>Table of Content</b>	<b>iv</b>
<b>List of Figures</b>	<b>v</b>
<b>List of Tables</b>	<b>vii</b>
<b>List of Abbreviations</b>	<b>ix</b>
<b>CHAPTER 1: INTRODUCTION</b>	<b>1</b>
1.1 Background	1
1.2 Removal of particles from water	2
1.3 Upward flow clarification	2
1.4 Justification for the study	3
1.3 Objective of the research	9
<b>CHAPTER 2: LITERATURE REVIEW</b>	<b>10</b>
2.1 Raw water turbidity and coagulation	10
2.2 Formation of particle structures within the blanket and settling velocity	14
2.3 Effect of Temperature variation	19
2.4 Sludge Cohesion Coefficient	23
2.5 Fluidization Theory	26
<b>CHAPTER 3: MATERIALS AND METHOD</b>	<b>27</b>
3.0 Sampling locations	27
3.0.1 Characteristics of raw water – Mahaweli River at Meewatura intake	27
3.1 Sample preparation	29
3.1.1 Preparation of synthetic raw water	29
3.1.2 Preparation of sludge samples	29
3.1.3 Equipment	29
3.2 Parameter to describe sludge blanket characteristics	30
3.2.1 Sludge Cohesion Test (SCT)	30
3.3 Effect of raw water quality on floc blanket formation	31
3.3.1 Floc blanket prepared with raw water	31

3.3.2 Pulsator® floc blanket .....	31
3.4 Effect of operating conditions on floc blanket and settling velocity .....	32
3.4.1 Tests using synthetic raw water .....	32
3.4.2 Preparation of coagulant dose .....	32
3.4.3 Trial tests .....	33
3.4.4 Test Series .....	34
3.4.5 Settling velocity .....	35
3.4.6 Testing at full scale using Pulsator® unit, Kandy South WTP .....	37
3.5 Formation of floc blanket and effect of temperature on the blanket .....	38
3.5.1 Laboratory tests using synthetic sludge samples.....	38
3.5.2 Testing at full scale Pulsator® floc blanket at Kandy South WTP .....	42
3.6 Pulsator® startup - Kandy South water treatment plant.....	43
3.6.1 Test plan.....	44
<b>CHAPTER 4: RESULTS AND OBSERVATIONS.....</b>	<b>47</b>
4.1 Effect of raw water quality on sludge blanket formation: .....	47
4.1.1 Floc blanket prepared with river water .....	47
4.1.2 Pulsator® floc blanket .....	48
4.2 Effect of operating conditions on the floc blanket and settling velocity.....	49
4.2.1 Trial tests using synthetic raw water .....	49
4.2.3 Test Series using synthetic raw water .....	50
4.2.4 Trial tests for settling velocity .....	53
4.2.5 Results- testing at full scale using Pulsator® unit Kandy South WTP ....	53
4.3 Formation of floc blanket and effect of temperature on the blanket .....	54
4.3.1 Laboratory testing using synthetic sludge samples.....	54
4.3.2 Testing at full-scale Pulsator® floc blanket at Kandy South WTP .....	58
4.4 Formation of the sludge blanket at pulsator startup, Kandy South WTP.....	59
<b>CHAPTER 5: DISCUSSION.....</b>	<b>63</b>
5.1 Effect of raw water quality on floc blanket formation: .....	63
5.1.1 Floc blanket prepared with river water .....	63
5.1.2 Pulsator® floc blanket .....	65
5.1.3 Floc blanket prepared with synthetic raw water .....	66
5.2 Effect of operating conditions on sludge blanket .....	68
5.2.1 Trial tests using synthetic raw water .....	68

5.2.2 Results of Test Series .....	69
5.2.3 Blanket settling velocity .....	77
5.2.4 Results of testing at full scale using Pulsator® unit Kandy South WTP .	79
5.3 Formation of floc blanket and effect of temperature on the blanket .....	80
5.3.1 Laboratory testing using synthetic sludge samples .....	80
5.3.2 Discussion- Testing at full scale- Pulsator® (25 <sup>th</sup> Dec 2016) .....	88
5.4 Formation of the floc blanket at pulsator start up, Kandy South WTP .....	94
5.4.1 Analysis of test results.....	94
5.4.2 Examining floc blanket characteristics using SCC .....	97
<b>CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS.....</b>	<b>103</b>
6.1 Raw water turbidity.....	104
6.2 Coagulant dose .....	104
6.2 Effect of inflow temperature .....	104
6.4 Particle settling mechanism within a floc blanket and settling velocity .....	105
6.5 Practical applications of this work .....	106
6.6 Recommendations for future studies: .....	107
<b>REFERENCES:.....</b>	<b>108</b>

## List of Figures

<b>Figure 2.1</b> - Schematic Pulsator Clarifier .....	24
<b>Figure 2.2</b> - Sludge cohesion coefficient.....	25
<b>Figure 3.1</b> - Raw water extraction locations; Mahaweli River .....	27
<b>Figure 3.2</b> - Variation of raw water turbidity at Meewatura intake, Mahaweli River .....	28
<b>Figure 3.3</b> - Variation of pH at Meewatura intake, Mahaweli River .....	28
<b>Figure 3.4</b> - Experimental Setup sludge cohesion test .....	31
<b>Figure 3.5</b> - Settling Test.....	36
<b>Figure 3.6</b> - Settling curve.....	36
<b>Figure 3.7</b> - Pulsator sectional view .....	37
<b>Figure 3.8</b> – (a) Grab sampler (b) Sampling .....	39
<b>Figure 3.9</b> – Experimental setup for blanket formation and effect of temperature variation.....	39
<b>Figure 3.10</b> - Variation of inflow velocity with time .....	41
<b>Figure 3.11</b> – Sludge volume test .....	41
<b>Figure 3.12</b> – Pulsator® floc blanket .....	41
<b>Figure 4.1</b> - Upward flow velocity $V_s$ vs apparent volume (Raw water at Meewatura 13.05.18) .....	47
<b>Figure 4.2</b> - Upward flow velocity vs apparent volume (Pulsator, Meewatura).....	48
<b>Figure 4.3</b> - Upward flow velocity vs apparent volume (Synthetic ; 397 NTU, PACl 10 ppm).....	49
<b>Figure 5.1</b> - Variation of SCC with (a) raw water turbidity (b) PACl dose .....	64
<b>Figure 5.2</b> - Variation of SCC with (a) raw water turbidity (b) PACl dose (Synthetic) .....	66
<b>Figure 5.3</b> - Variation of SCC with raw water turbidity (All data).....	67
<b>Figure 5.4</b> - Residual turbidity versus coagulant dose observed in jar tests .....	69
<b>Figure 5.5</b> - Schematic representation of coagulant observed in jar tests (Weber 1972).....	70
<b>Figure 5.6</b> - SCC vs coagulant dose obtained in sludge cohesion test.....	71
<b>Figure 5.7</b> - Residual turbidity versus coagulant dose (250-550 NTU).....	72
<b>Figure 5.8</b> - SCC vs coagulant dose (250 – 550 NTU) .....	72
<b>Figure 5.9</b> - Optimum coagulant dose at jar test and SCC test vs raw water turbidity .....	73
<b>Figure 5.10</b> - Relationship between the optimum coagulant doses.....	74
<b>Figure 5.11</b> - Residual turbidity versus coagulant dose (250 – 550 NTU) .....	75
<b>Figure 5.12</b> - SCC vs coagulant dose (250-550 NTU).....	76
<b>Figure 5.13</b> – Relationship between optimum coagulant doses of the two tests.....	77
<b>Figure 5.14</b> - Variation of blanket cohesivity and the settling vel.with coagulant dose & SCC.....	78
<b>Figure 5.15</b> - Variation of settling velocity with SCC .....	78
<b>Figure 5.16</b> - Variation of SCC and $V_s$ with time of the day .....	79

<b>Figure 5.17</b> - Variation of SCC and $V_s$ with depth .....	79
<b>Figure 5.18</b> - Variation of settling velocity with SCC (All data) .....	80
<b>Figure 5.19</b> - Variation of blanket height and effluent turbidity with time Experiment 1 .....	81
<b>Figure 5.20</b> - Variation of blanket height and effluent turbidity with time Experiment .....	83
<b>Figure 5.21</b> – Variation of blanket height, effluent turbidity, and Inflow temperature with time .....	86
<b>Figure 5.22</b> – (a) Floc blanket height, effluent turbidity, Inflow and outflow temperature variation with time, (b) Expansion of sludge blanket .....	86
<b>Figure 5.23</b> - Variation of (a) temperature with time (b) effluent turbidity with time .....	87
<b>Figure 5.24</b> - Variation of effluent turbidity with temperature .....	88
<b>Figure 5.25</b> - Variation of temperature with time .....	89
<b>Figure 5.26</b> - Variation of influent and effluent turbidity with time .....	89
<b>Figure 5.27</b> - Variation of effluent turbidity with (a) raw water temperature (b) average blanket temperature .....	90
<b>Figure 5.28</b> - Variation of blanket sludge volume with temperature .....	91
<b>Figure 5.29</b> - Variation of SCC with blanket temperature .....	92
<b>Figure 5.30</b> - Variation of $V_s$ with (a) blanket temperature (b) SCC .....	92
<b>Figure 5.31</b> - Variation of raw water and effluent (Pulsator) turbidity with time .....	95
<b>Figure 5.32</b> – Formation of floc blanket .....	925
<b>Figure 5.33 (a,b,c,d)</b> - Variation of (a) SV (%), (b) $V_s$ , (c) SCC, and (d) effluent turbidity variation with time (days) .....	96
<b>Figure 5.34</b> - Variation of the ratios of $V_s$ to SCC [i.e., $V_s/SCC$ (field data)] and $V_s$ to $V_t$ [i.e., $V_s/V_t$ (using equation of Richardson and Zaki)] with $(1 - SV)$ and $Re$ .....	98
<b>Figure 5.35</b> - Variation of $V_s$ with SV (a) and SCC (b) .....	99
<b>Figure 5.36</b> - Variation of SCC with SV .....	100

## List of Tables

<b>Table 1.1:</b> Values for the Richardson & Zaki index $m$ : .....	26
<b>Table 3.1</b> - Sampling details; effect of raw water quality.....	31
<b>Table 3.2</b> - Sampling details; Pulsator, Kandy South Water Treatment Plant.....	32
<b>Table 3.3</b> - Trial tests on synthetic sludge for SCC.....	33
<b>Table 3.4</b> – Trial tests on synthetic sludge for settling velocity.....	34
<b>Table 3.5</b> - Raw water turbidity 20 – 200 NTU- Test series 1 .....	34
<b>Table 3.6</b> - Raw water turbidity 250 – 500 NTU - Test series 2 .....	35
<b>Table 3.7</b> – Raw water turbidity 250-500 NTU- Test Series 2 (Repeat) .....	35
<b>Table 3.8A</b> - Parameters measured/ tested.....	37
<b>Table 3.8B</b> - Test plan at the Pulsator sludge blanket.....	38
<b>Table 3.9</b> - Summary of test series.....	40
<b>Table 3.10</b> - Testing programme of the pulsator startup.....	44
<b>Table 4.1</b> - Raw water characteristics, coagulant dose and SCC.....	47
<b>Table 4.2</b> - Sludge cohesion of samples taken at pulsator floc blanket, Kandy South WTP.....	48
<b>Table 4.3</b> - Results of trial tests (SCC in m/hr).....	50
<b>Table 4.4</b> - Supernatant turbidity after jar test and sludge cohesion coefficient SCC (m/hr).....	50
<b>Table 4.5</b> - Supernatant turbidity after jar test and average SCC (m/hr).....	51
<b>Table 4.6</b> - Supernatant turbidity after Jar Test and Sludge Cohesion Coefficient (m/hr) - Repeat test.....	52
<b>Table 4.7</b> - Settling velocity of particles.....	53
<b>Table 4.8</b> - Field testing at Kandy South Pulsator (SCC m/hr, $V_s$ mm/sec).....	53
<b>Table 4.9A</b> - Experiment 1 Variation of floc blanket height and effluent turbidity until the water reached outflow level (Up flow velocity 2.63 mm/sec).....	54
<b>Table 4.9B</b> - Experiment 2 Variation of inflow velocity, floc blanket height and effluent turbidity.....	55
<b>Table 4.9C</b> - Experiment 3, Variation of inflow temperature, sludge blanket height and effluent turbidity (Upward flow velocity 2.94 mm/sec).....	56
<b>Table 4.9D</b> - Experiment 4, Variation of inflow temperature, sludge blanket height and effluent turbidity (Upward flow velocity 4.25 mm/sec).....	57
<b>Table 4.10</b> - Variation of inflow and Sludge blanket characteristics.....	58
<b>Table 4.11</b> - Pulsator startup at Kandy South water treatment plant; RWT & EFT data....	60
<b>Table 4.12</b> - Pulsator startup at Kandy South water treatment plant (1-6 days), RWT, Flow, Pulsation and turbidity at three layers (prior to formation of blanket).....	61

<b>Table 4.13</b> - Pulsator start up at Kandy South water treatment plant (7-16 days), RWT, Pulsation rate and SVF, SCC and $V_s$ of all three layers (after blanket formation started from the bottom layer).....	62
<b>Table 5.1</b> – Relationship between RWT and SCC.....	64
<b>Table 5.2</b> - Optimum coagulant dose and respective values at each test.....	73
<b>Table 5.3</b> - Optimum coagulant dose derived from the two tests.....	76
<b>Table 5.4</b> - Statistical Analysis – Effect of influent quality parameters on effluent...	91
<b>Table 5.5</b> - Statistical analysis – Dependence of SCC, $V_s$ on temperature.....	93

### List of Abbreviations

Al	- Aluminum
V	- Apparent Volume
V <sub>s</sub>	- Blanket Settling (Sedimentation) Velocity
R <sup>2</sup>	- Coefficient of Determination
ρ	- Density of Fluid
D	- Drafting
μ	- Dynamic Viscosity
EFT	- Effluent Turbidity
m	- Empirical Exponent
Fe	- Ferric
KMC	- Kandy Municipal Council
K	- Kissing
G	- Mixing Intensity (Shear Rate)
NWS & DB	- National Water Supply & Drainage Board
NTU	- Nephelometric Turbidity Units
C	- Particle Concentration
d	- Particle Diameter
r	- Pearson Correlation Coefficient
PACL	- Poly Aluminum Chloride
pH	- Potential of Hydrogen
RWT	- Raw Water Turbidity
rpm	- Revolutions Per Minute
Re	- Reynolds Number
∞	- Significance Level
h <sub>1</sub>	- Sludge/Clear
SCC (K)	- Sludge Cohesion Coefficient
SCT	- Sludge Cohesion Test
h	- Sludge Height
SV (SVF)	- Sludge Volume Fraction
SVT	- Sludge Volume Test
U <sub>s</sub>	- Superficial Velocity
V <sub>t</sub>	- Terminal Settling Velocity
t	- Time
T	- Tumbling
u	- Upward Velocity
Φ	- Void age
V <sub>0</sub>	- Volume at Zero Velocity