Image based analysis of settling experiments

Master Project Spring Term 2014

Picture: Standard set-up of Sludge Volume Experiment

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1 Introduction

Today's designing and operation of secondary clarifiers in conventional activated sludge (AS) biological waste water treatment plants (WWTPs) are either based on the experience of the designer with similar suspended growth settling characteristics or characteristic sludge parameters describing the settling process. Parameters describing the thickening and settling process can be assumed considering data from other WWTPs or by applying fundamental techniques to link test results to clarifier design. [10]

There are two commonly used parameters to quantify the settling characteristics of activated sludge. The sludge volume index (SVI) and the zone settling velocity (v_{zs}), also known as Type III settling velocity [10]. Both can be obtained by a simple settling test. The SVI mainly determines the volume of the secondary clarifier for effective sludge thickening [8] and serves as a comparable number between different sludge types [3]. The settling velocity is used to calculate the surface overflow rate (SOR) which determines the maximal return flow rate from the settler to the main biological reactor without risking losses via the effluent [8]. Adequate clarification of the effluent and solids thickening is required.

Once the dimensioning of the settler is done, its performance is controlled by measuring the SVI on a weekly basis. The sludge volume (SV) is read by a human operator and the total suspended solids (TSSs) are measured in the laboratory to compute the SVI. The settling velocity is not registered. [8]

Simple modern digital cameras offer an opportunity to register sludge volume and settling velocity on an efficient and reliable basis. By sequencing images in a standard tool – such as Matlab – the SV can be read and the settling velocity tracked. Automated data logging enables a frequent evaluation of the settling volume and the settling velocity. This conduces to a performance-evaluation of the secondary clarifier. [8]

Exploring and evaluating the opportunities and limits of image processing for reliable parameter estimation of the settling tank are the focus of this report. Advantages and disadvantages as well as the limits of this promising measurement method are analyzed and presented in the following.

2 THEORY

2.1 SLUDGE VOLUME INDEX

The sludge volume index is defined as the volume taken by 1 g of sludge after 30 min of settling [10].

$$SVI = \frac{settled\ volume\ of\ sludge}{suspended\ solids}\ [\frac{mL}{g}]$$

The experiment of sludge settling leading to the SV, combined with a total suspended solids (TSS) measurement permits to calculate the SVI [10].

2.2 HINDERED (ZONE) SETTLING VELOCITY

The zone settling velocity can be determined by tracking the sludge blanket during the experiment [8] while different settling zones are observed. *The height of the sludge blanket is defined as the location of the uppermost layer with a sludge concentration higher than a certain threshold* [3]. Whereas discrete, flocculent, hindered and compression settling are possible, only Type III and Type IV settling are usually observed during sludge settling experiments with sludge from the secondary settling tank (cf. Figure 1 (a)) [10].

The hindered zone settling velocity corresponds to the slope of the tracked sludge blanket height during the settling experiments (cf. Figure 1 (b)). The descent of the blanket depends only on the equilibrium between gravitational and hydraulic friction forces. [3]

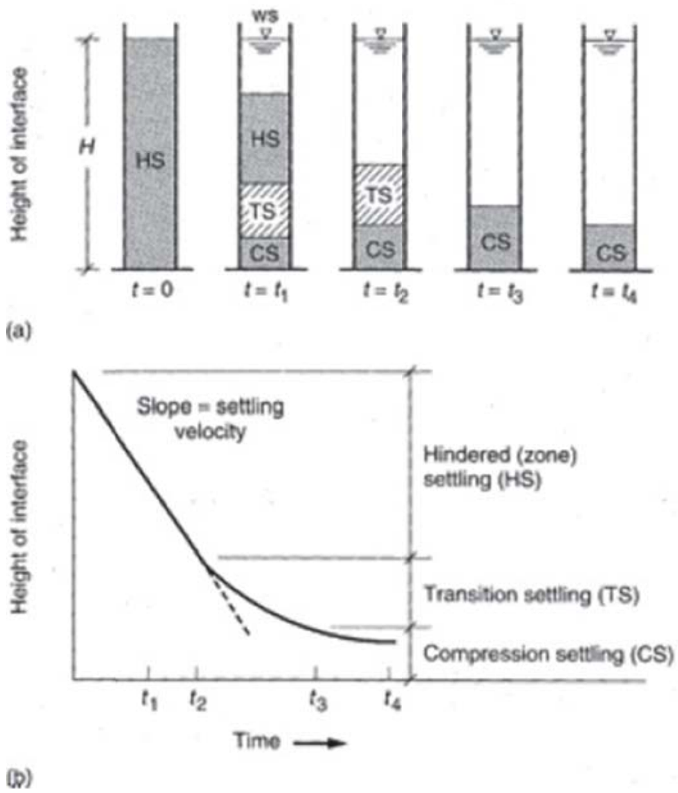

FIGURE 1 : DEFINITION SCETCH FOR HINDERED (ZONE) SETTLING: (A) SETTLING COLUMN IN WHICH THE SUSPENSION IS TRANSITIONING THROUGH VARIOUS PHASES OF SETTLING AND (B) THE CORRESPONDING INTERFACE SETTLING CURVE (SOURCE: METCALF AND EDDY [10])

3 METHOD

The main focus of this project is on exploring the opportunity of determining sludge volume taken by the sludge after a 30 min settling experiment using a simple modern digital camera. Several experiments with different incident angles and light adjustments were conducted. By processing this data, the issues of image analysis and its opportunities can be explored. Parameters such as SV and v_{zs} are determined, and their accuracy analyzed. Nevertheless, the total solids in the liquor sample is measured first of all in the laboratory to finally allow for SVI calculation.

3.1 TOTAL SOLIDS MEASUREMENT

A filter paper (MN 640 w, Ø 90 mm) is filtered with a distilled water sample and dried during 1 hour at 105°. After the cooling in the exsiccator it's weighted. 100 ml of sludge is taken from the top layer of the 4l sludge liquor sample mixed at 500 turns/min and filtered through. Particles staying at the border are washed through the filter with distilled water. The filter with the suspended solids on top is folded and dried at 105° until it reaches a constant weight. After the cooling in the exsiccator the filter is measured and the total solids weight can be determined.

$$TS = \frac{filter\ with\ leavings\ after\ drying - empty\ filter}{100\ ml} * \frac{1000\ ml}{1\ l}\ [\frac{mg}{l}]$$

3.2 SLUDGE VOLUME DETERMINATION

3.2.1 SERIES COLLECTION

A 1 l and a 2 l glass column are placed in front of the camera and filled with the liquor sample. During 30 min of settling experiment a picture is taken every 15 s leading to a sequence of 120 pictures per experiment. Deciding on a standard set-up allows the comparison of four sludge-types whereas one sludge sample is analyzed to compare the different settings of the experiments incident angle and another sludge sample is analyzed to compare different light conditions on the automated determination of sludge volume. Blue scotches represent top and bottom of the class cylinder with blue tape markings .

The set-up of the experiment is always kept simple and practical (cf. Figure 2). Thinking of the opportunities of image processing, the background of the image was white and homogeneous.

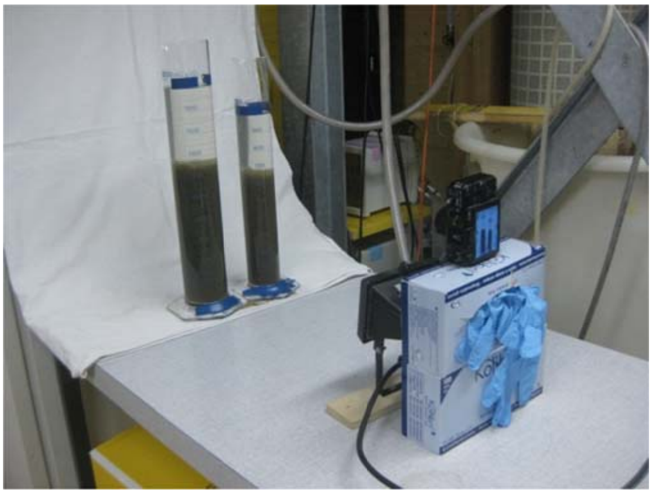

FIGURE 2 : PICTURE SEQUENCING SET UP

Seven experiments with different camera incident angle and light conditions are conducted. Camera settings and the position of the cylinder are constant as they are supposed to have no influence of importance on the accuracy of measurement. The picture size is of normal resolution (1944 X 2592) and the quality is fine compression. For the standard set, flash is forbidden as it requires energy and effects reflection on the glass cylinder in addition. Another reason beside the energy and memory savings of the standard set-up is the sharply detected interface of the sludge blanket during color channel analysis tested in parallel to the execution of the experiments (cf. Annexe A7).

Playing with additional light leads to three more settings aside the standard light settings. Standard light settings consist in neon light of the experimental hall (EH) at Eawag where the experiments are conducted. A flood light is installed in front of the cylinders for a sequence of image (cf. Figure 2). For another sequence the flood light is placed behind the white blanket to equally emblaze the cylinder from the back. For the 4^{th} sequence the flash of the camera is used in addition to the standard set-up.

TABLE 1 : PARAMETERS OF THE EXPERIMENT AND THE STANDARD SET-UP

Parameter	Standard Set -Up
Camera Settings	Fine, M2, no flash
Camera Position	In front of cylinder engraving, vertical, at average column height
Light	Neon light of experimental hall, no extra light
Cylinder	In front of white at a horizontal distance of 1 m to the camera

The second varying parameter is the incident angle of the camera focus respect to the cylinder. During the standard set-up experiment the camera is placed at the average height of the 2l column and at a horizontal distance of 1 m (cf. Figure 2). Later on, the camera is placed on the table, on the ladder 45 cm above the top of the 2l column and at a horizontal distance of 2.3 m. Camera at 2.3 m, a sequence of picture with zoom and a sequence without zoom is taken. Putting the camera on top of the 2l column and taking pictures from above to detect the sludge blanket through the remaining liquid is the last experiment of this serie.

The standard set-up is applied to four different sludge samples to compare the method based on different sludge settling characteristics.

TABLE 2 : EXPERIMENTS CONDUCTED

Variable	Standard	Front flood light	Back flood light	Flash	Camera on table	Camera on ladder	Camera at 2.3 m, Zoom	Camera at 2.3 m, no Zoom	Camera on top of column
Sludge Tank 1 EH	x	x	x	x					
Sludge Tank 2 EH	x				x	x	x	x	x
Sludge Urin Tank	x								
Sludge WWTP Winterthur	x								

3.2.2 Image Processing

The software Matlab in the version R2010a is used for image analysis. The JPEG picture sequences are read by the software and standard tools for the detection of transient areas are applied.

The *canny edge* detector and the *hough* transform are tested. The *canny edge* detector takes an intensity image and returns a binary image with ones where edges are detected. The *hough* transform is able to detect lines and is applied to the binary edge image to highlight the visually observed transient areas. But as the interface of the sludge blanket is not a sharp, straight line and in addition the cylinder adds a rounded shape, the *hough* transform to detect straight lines is not well adapted.

Images are saved in a matrix format of 3 dimensions. The 3rd dimension consists of the optical separation of the color channels red, green and blue (RGB). This intensity channels are analyzed along a vertical line through the column (cf. Figure 3). The sludge blanket as well as the top and the bottom of the column could be detected (cf.Figure 4). The successful method of detecting transient areas earned it to be pursued.

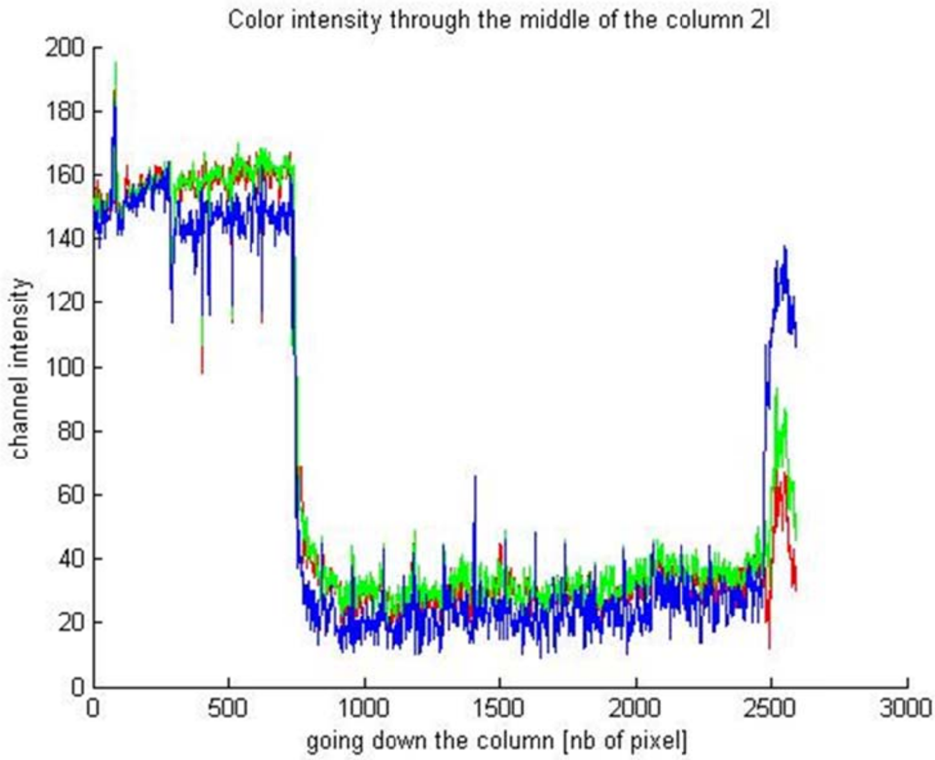

FIGURE 3 : RED GREEN BLUE CHANNEL INTENSITY ANALYSIS OF SLUDGE FROM TANK 1 THROUGH THE MIDDLE OF THE COLUMN 2L WITH SLUDGE FROM TANK 1 AND STANDARD SET-UP

Looking at Figure 3 one can see the brightness of the colors on the left where the liquid is. Going down the column meaning going to the right on the picture, the color intensities drop all of a sudden meaning the liquid – solid interface is detected. They stay small until the bottom is reached where the blue scotch is observed and showing up as a high blue intensity on the right side of the graph. The sludge blanket is detected on each picture when the color intensity drops below a certain threshold. Defining this threshold consists in a delicate task as it highly influences the accurateness of the computation.

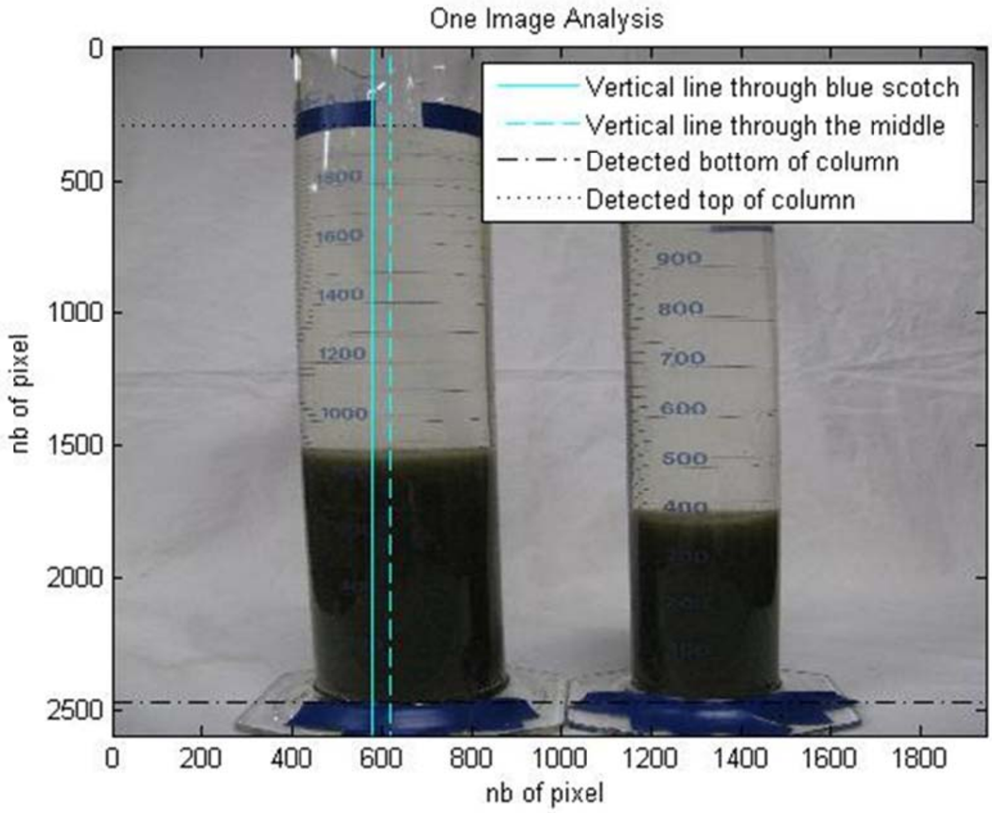

FIGURE 4 : VERTICAL LINES THROUGH THE 2L SLUDGE COLUMN SERVING TO DETECT THE BOTTOM AND THE TOP OF THE GRADUATION OF THE COLUMN WITH SLUDGE FROM TANK 1 AND STANDARD SET-UP.

Threshold is defined as the mean of the red, green, blue channel intensities detected on the whole column height of the first picture. By settling the sludge becomes denser and thus has tendency to be of lower intensity, which means the threshold defined as the mean of the three channel intensities of the liquor sample not jet settle is reasonable.

$$Threshold = mean\left(\frac{Red + Green + Blue}{3}\right)$$

But first of all the bottom and top have to be localized. By looking at the color intensities along the line through the blue scotch, a sequence of pixels with higher blue color intensity than red or green color intensity is determined to represent the bottom or the top of the image.

Being able to detect accurately the hindered settling zone an exponential function is selected to describe the settling process.

$$H = a * e^{\frac{b}{t+t_c}} \qquad [m]$$

H describes the height of the sludge blanket [m], a is dependent on the ultimate height of the sludge blanket [m] and b is related to the settling characteristics of the sludge [h]. t_c is the critical time [h] where the zone settling stops and compression settling begins. Transient settling is supposed to be negligible.

Before the equation is fitted to the raw computed data, a filter is applied to eliminate the erroneous influence of the outliers to the parameters. The implemented Matlab filter *rlowess* which combines multiple regression models in a 5-nearest-neighbor-based meta-model is used. Based on least squares linear regression this filter is able to incorporate the outliers in the computed settling. Another method could consist in completely erasing them before fitting a curve to it.

The sludge settling curve is calculated for the observed data to draw a confidence interval of 95 % around the data and to calculate the desired sludge parameter. The 95 % confidence interval is a measure of the reliability of the estimate. 95 % of the observed data should lie within the bounds if the fitted curve is adapted to the settling behavior of the sludge. If the model performs well, 95 % of estimated sludge blanket heights should lie within the confidence interval of the observed data. Anticipating that the sludge settling model is only adapted to settling behavior going from hindered settling to compression settling within a reasonable time frame, confidence interval of linear polynomial function fitted to the observed data are drawn. Threshold of t_c being small enough to allow an exponential curve fit is set to 1 hour. If this threshold is exceeded, linear regression is used to draw the confidence bounds of 95 %.

The hindered (zone) settling velocity v_{zs} corresponds to the derivation of the settling curve during this phase. Setting up the experiment, an initial lag stage of the decrease of the sludge blanket can be observed and have to be treated separately. The end of lag phase is determined as the minimum local deviation. The initial lag stage influences the curve in the beginning thus a linear regression of the data points between the end of lag stage and the critical time is calculated. The slope of the first degree polynomial corresponds to the hindered settling velocity. Where settling occurs to fast, the last data point of lag stage is added.

The method to calculate the v_{zs} above leads to only one value, but as the method allows the velocity estimation during the whole settling experiment. Velocity can be tracked during time and as well during concentration changes. Assuming that the sludge concentration is homogeneous and all sludge is concentrating under the sludge blanket, the concentration of the sludge during the experiment can be estimated from the conservation of mass.

$$Concentration = \frac{H_0}{H} * Concentration_0$$

Evaluating the statistical importance of the obtained value not only on the drawn confidence intervals, the Percent Bias (PBIAS) is computed. Percent bias measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (*Gupta et al., 1999*). It expresses the deviation of the computed data in percentage.

$$PBIAS = \frac{\sum_{i=0}^{n}\left(Y_i^{obs} - Y_i^{comp}\right) * 100}{\sum_{i=0}^{n}\left(Y_i^{obs}\right)} \quad [\%]$$

Positive values indicate model underestimation bias whereas negative values indicate model overestimation. Optimal model performance has percent bias equal to zero and absolute small values indicate good model performance.

The computation time is registered after every run to evaluate the method on its speed.

The method is evaluated based on the 2 l column sludge settling experiment.

4 RESULTS

The method leads to different model performance depending on sludge characteristics. The sludge volume of tank 1 of the experimental hall is underestimated with a constant off set (cf. Figure 5). The computed data does not show up in the confidence interval of the observed height even though a polynomial curve fit of 1st degree is used to draw the confidence bounds as $t_c > 1$ h. Sludge volume form tank 2 and sludge volume from the WWTP Winterthur show up to be slightly underestimated which disagrees with the computed percent bias for the sludge from tank 2 (cf. Table 3) . Both lie in the confidence interval of 95 %. The interface of the liquid – solids separation of the urine tank could not be detected (cf. Annexe 10). Sludge settling velocity cannot be detected and the SVI estimation is not accurate.

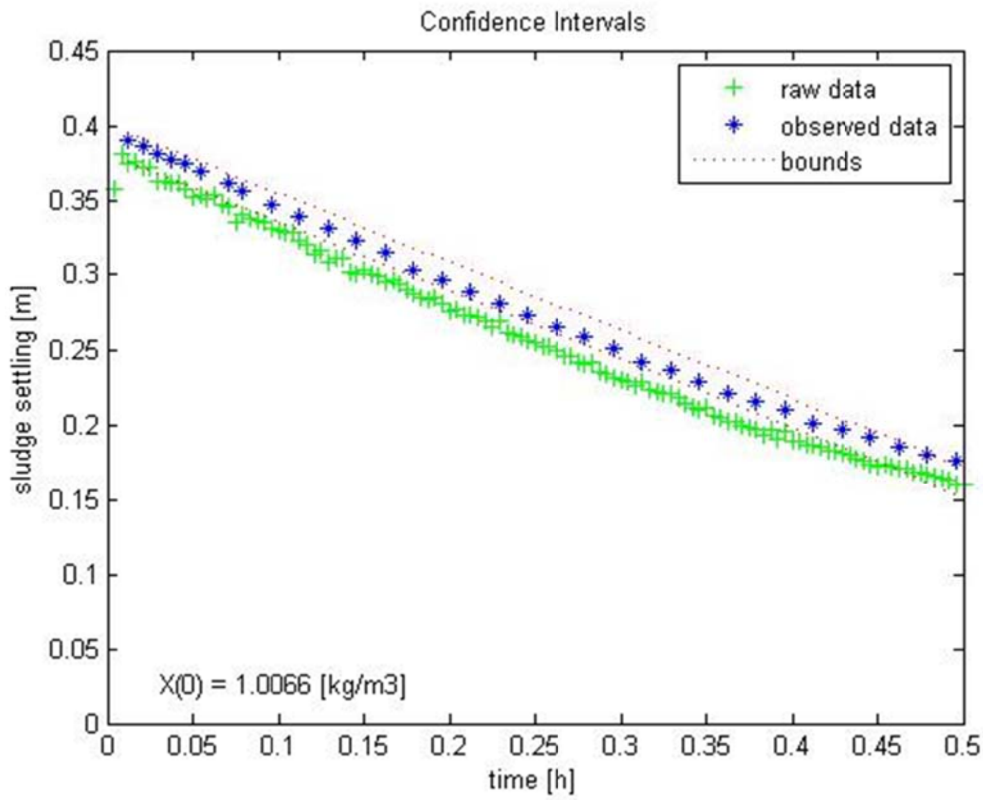

FIGURE 5 : SLUDGE SETTLING CURVE OF RAW COMPUTED DATA VERSUS OBSERVED DATA WITH ITS CONFIDENCE BOUNDS OF 95 %. SLUDGE FROM TANK 1, STANDARD SET-UP

The estimated parameters are in range with the observed ones (cf. Table 3). The PBIAS is only able to compare data where the sludge blanket height is observed, which means not at every data point computed. This may give a wrong idea of the under – and overestimation of model performance as on erroneous computation can shift the PBIAS significantly.

Tendency of settling velocity being high when critical time of the end of the hindered settling zone is low can be observed. SVI and PBIAS do not show up any correlation. (cf. Table 3)

TABLE 3 : OBSERVED AND SIMULATED PARAMETERS OF SETTLING EXPERIMENT FOR THE 4 DIFFERENT TYPES OF SLUDGE

Standard Sets	$t_{c,obs}$ [h]	$t_{c,sim}$ [h]	$v_{zs,obs}$ [m/h]	$v_{zs,sim}$ [m/h]	SVI_{obs} [ml/g]	SVI_{sim} [ml/g]	PBIAS [%]
Sludge Tank 1 EH	5.30	8.29	0.50	0.48	256.34	236.82	+5.8
Sludge Tank 2 EH	0.12	0.11	3.73	3.86	97.24	94.44	-6.6
Sludge WWTP Winterthur	0.06	0.05	5.73	6.24[1]	99.71	103.80	+1.8
Sludge Urin Tank	0.02	0.28	0	0	97.63	831.61	-375.2

Additional illumination from the front of the cylinder is able to shift the estimates to the height of the observed data when being underestimated before. Nevertheless in the starting phase of the sludge settling the interface cannot be detected (cf. Figure 6). Reflection of light on the cylinder can lead to errors when channel analysis is made along the line through the reflections.

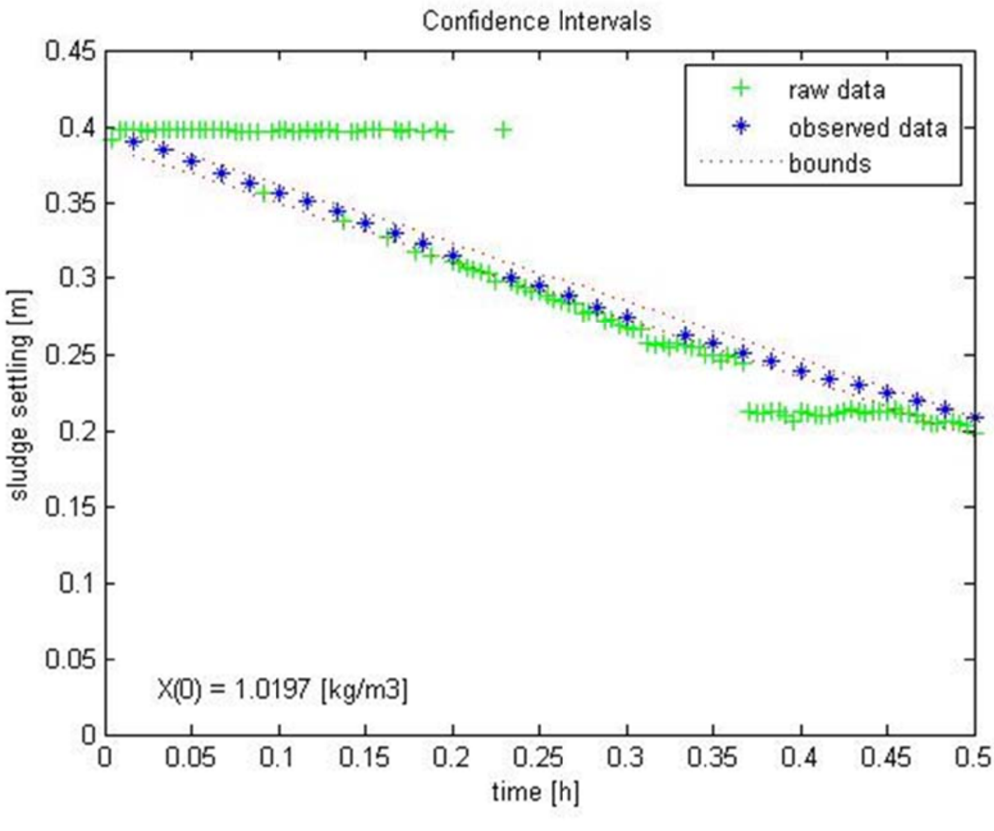

FIGURE 6 : SLUDGE SETTLING CURVE OF RAW COMPUTED DATA VERSUS OBSERVED DATA WITH ITS CONFIDENCE BOUNDS OF 95 %. SLUDGE FROM TANK 1, FLASH

The ability of additional illumination of the sludge volumes to raise the computed sludge volume heights to the observed ones is confirmed by the percent bias measurement (cf. Table 4). The standard set-up and the standard set-up plus back flood light are underestimated. Underestimation leads to lower SVI measurement, overestimation leads to higher SVI measurement.

[1] Last data point of lag stage was added to compute the hindered settling velocity

The tendency of hindered settling velocity being lower when critical time being higher can be confirmed. The velocity could not be estimated accurately for sludge blanket tracking with starting problems (cf. Figure 7).

TABLE 4 : OBSERVED AND SIMULATED PARAMETERS OF SETTLING EXPERIMENT FOR THE FOUR DIFFERENT LIGHT SETTINGS. SLUDGE FROM TANK 1

Sludge Tank 1	$t_{c,obs}$ [h]	$t_{c,sim}$ [h]	$v_{zs,obs}$ [m/h]	$v_{zs,sim}$ [m/h]	SVI_{obs} [ml/g]	SVI_{sim} [ml/g]	**PBIAS** [%]
Standard	5.30	8.29	0.50	0.48	256.34	236.82	+5.8
Front flood light	4.67	8.37	0.50	1.06	229.31	239.31	-7.5
Back flood light	4.77	6.93	0.43	0.40	258.90	245.15	+4.8
Flash	4.69	9.67	0.40	1.12	277.84	283.59	-3.2

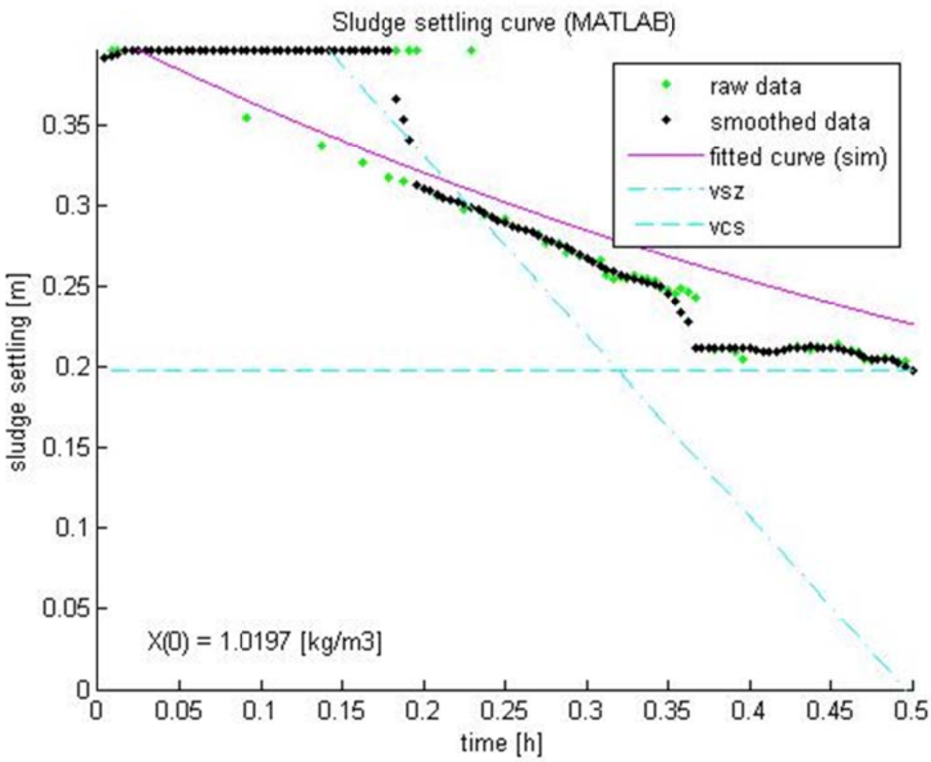

FIGURE 7 : SLUDGE SETTLING CURVE OF RAW COMPUTED DATA AND THE FILTERED RAW DATA AND THE EXPONENTIAL CURVE FIT. ESTIMATED ZONE SETTLING VELOCITY (VSZ) AND COMPRESSION SETTLING VELOCITY (VCS) ARE DETECTED. SLUDGE FROM TANK 2, FLASH

The different settings of the camera incident angle and the light conditions show up to have a big influence on model performance too. Taking pictures from the bottom of the column towards the sludge blanket the height is overestimated, tanking pictures form above the height of the sludge blanket estimates are too small which is accurately pointed out by the percent bias measurement (cf. Table 5). Taking pictures from a horizontal distance of 2.3 m and applying a zoom, the model performs well. Few outliers are observed.

TABLE 5 : OBSERVED AND SIMULATED PARAMETERS OF SETTLING EXPERIMENT FOR THE FOUR DIFFERENT INCIDENT ANGLES. SLUDGE FROM TANK 2

Sludge Tank 2	$t_{c,obs}$ [h]	$t_{c,sim}$ [h]	$v_{zs,obs}$ [m/h]	$v_{zs,sim}$ [m/h]	SVI_{obs} [ml/g]	SVI_{sim} [ml/g]	PBIAS [%]
Standard	0.12	0.11	3.73	3.86	97.24	94.44	-6.6
Camera on table	0.12	0.17	3.30	2.65	105.66	120.31	-7.6
Camera on ladder	0.16	0.11	3.23	3.33	123.77	118.20	+6.2
Camera at 2.3 m, Zoom	0.11	0.16	3.35[2]	3.21	135.04	127.55	-2.6

Tanking pictures form above leads to a scattering beside the constant underestimation of the sludge blanket height (cf. Figure 8). The interval of confidence is large.

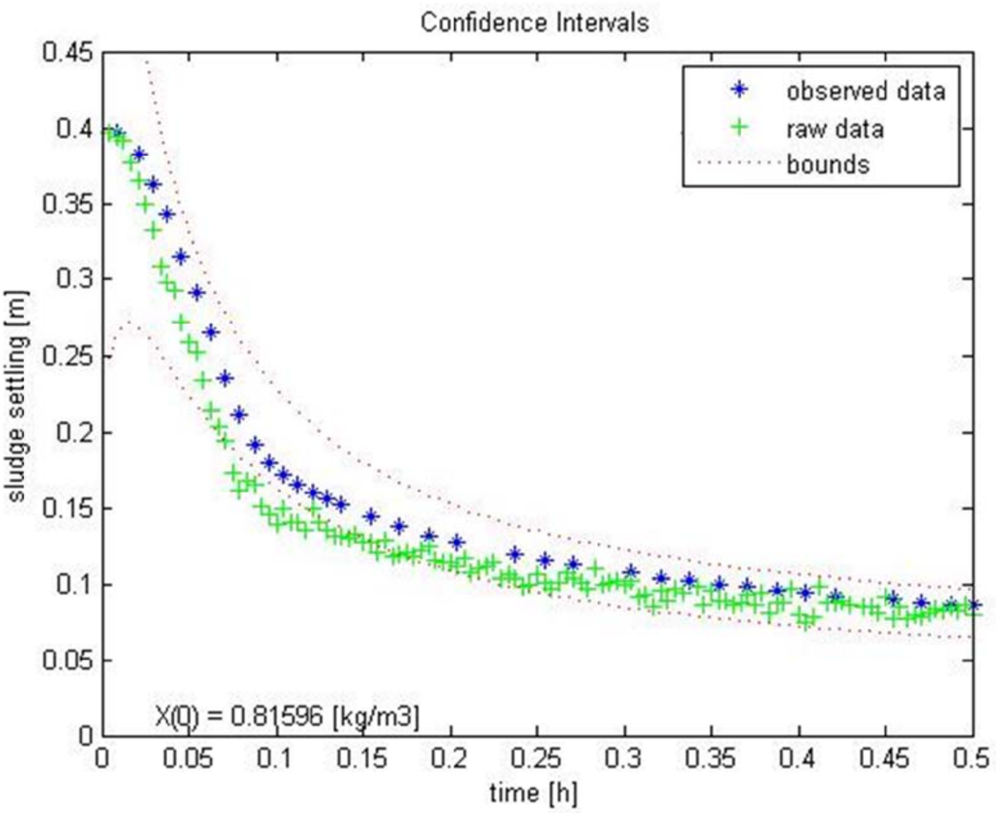

FIGURE 8 : SLUDGE SETTLING CURVE OF RAW COMPUTED DATA VERSUS OBSERVED DATA WITH ITS CONFIDENCE BOUNDS OF 95 %. SLUDGE FROM TANK 2, CAMERA ON LADDER

Further the accuracy of the curve fit method is looked at. When different stages of sludge settling is observed during the 30 min settling experiment the selected curve fit seams adequate. The curve converges to the values. Problems are detected during the lag phase and the transition settling. When initializing the settling, the curve starts at infinity and the curvature of the of the transition settling is not represented accurately (cf. Figure 9). When only type III settling occurs, a linear model would represent better the shape of the settling process over time. The exponential model diverges from data points (cf. Figure 7).

[2] Last data point of lag stage was added to compute the hindered settling velocity

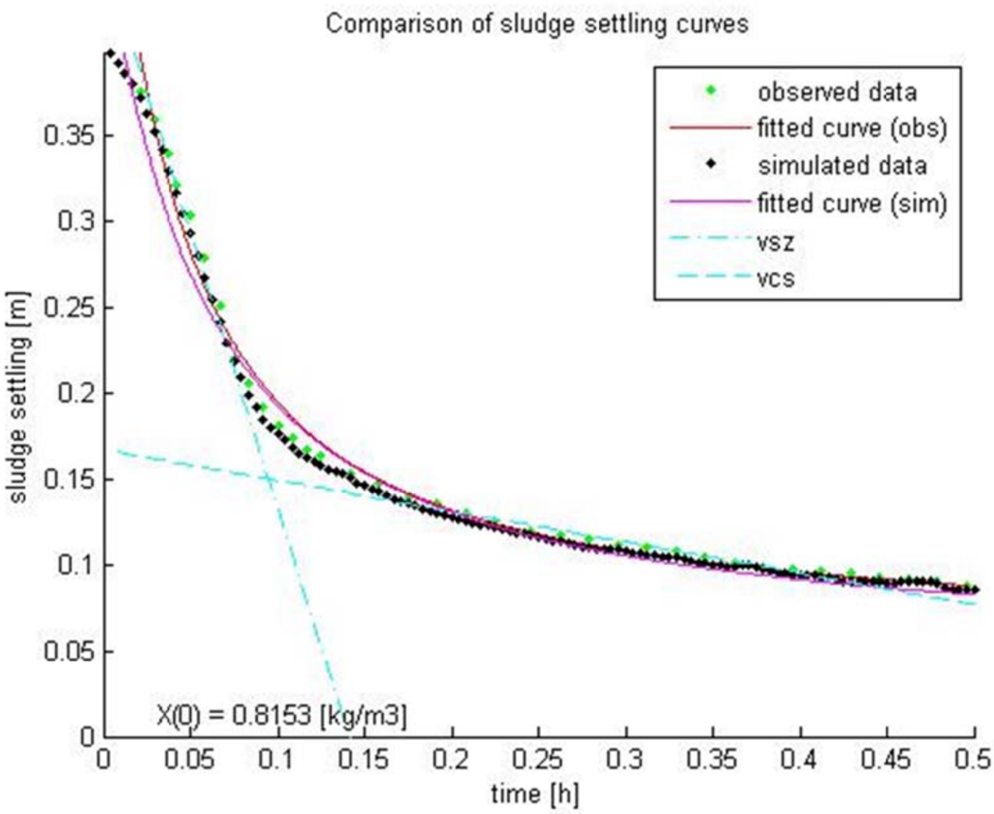

FIGURE 9 : SLUDGE SETTLING CURVE OF THE OBSERVED DATA, THE FILTERED RAW DATA AND THEIR EXPONENTIAL CURVE FIT. ESTIMATED ZONE SETTLING VELOCITY (VSZ) AND COMPRESSION SETTLING VELOCITY (VCS) ARE DETECTED. SLUDGE FROM TANK 2, CAMERA AT 2.3 M, ZOOM

Zone settling velocity is observed during the zone settling phase and consists of a constant value. Image processing allows for tracking the velocity during the experiment and determine it continuously for the changing concentration conditions of the liquor sample in the column.

The settling velocity of the sludge tank 1 is decreasing slowly at about 0.5 m/h on a constant scale. Scattering of the detected velocity is observed up to a value of 2 m/h. Smoothing out the computed data the shape equals almost the observed data settling velocity. By plotting the computed settling velocity over the concentration, no specialty is detected. Constant thickening of the sludge occurs with constant decreasing settling velocity reaching the final concentration of around 2.35 kg/m^3.

The settling velocity of the sludge tank 2 is raising during the lag stage reaching its maximum after the lag time. V_{zs} decreases fast until the hindered zone settling goes over to the transition settling and finally to the compression settling zone. The behavior of the decreasing sludge blanket is detected by the computed values but the fitted curve assumes infinite settling velocity at the beginning of the experiment. Once again raw computed data is scattering around the observed data. Plotting the computed settling velocity over the concentration fast thickening is detected during the hindered settling process. Going over to the compression settling, sludge settling velocity can occur at several sludge concentrations. After 30 min the concentration of 4.15 kg/m^3 is reached.

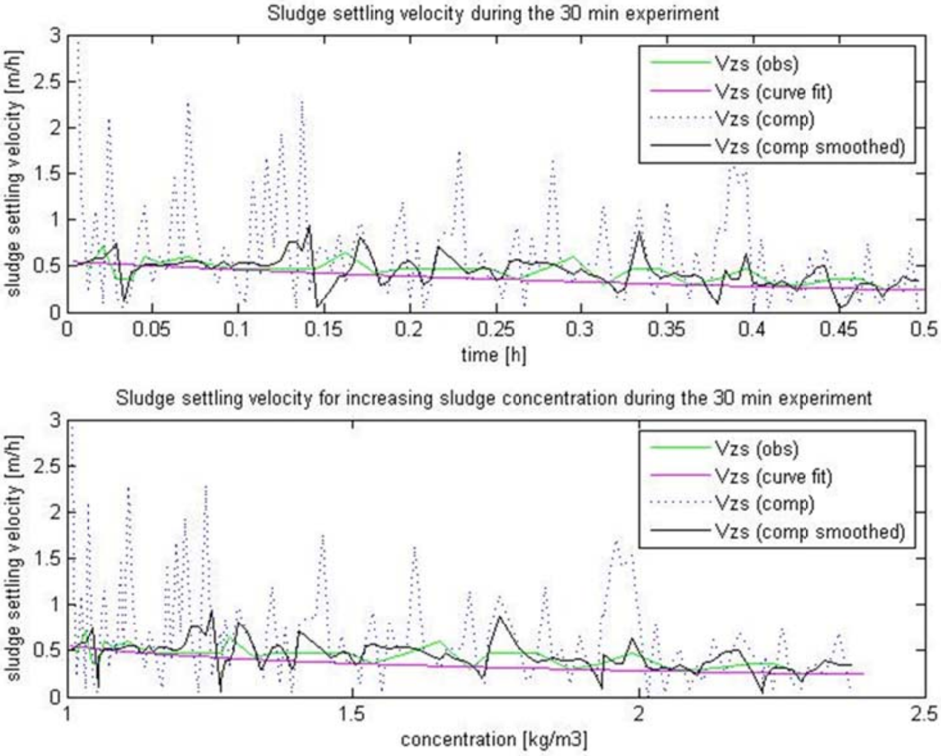

FIGURE 10 : TRACKED SLUDGE SETTLING VELOCITY DURING THE 30 MIN SETTLING EXPERIMENT AND DURING CHANGING CONCENTRATION CONDITIONS. SLUDGE TANK 1, STANDARD SET-UP

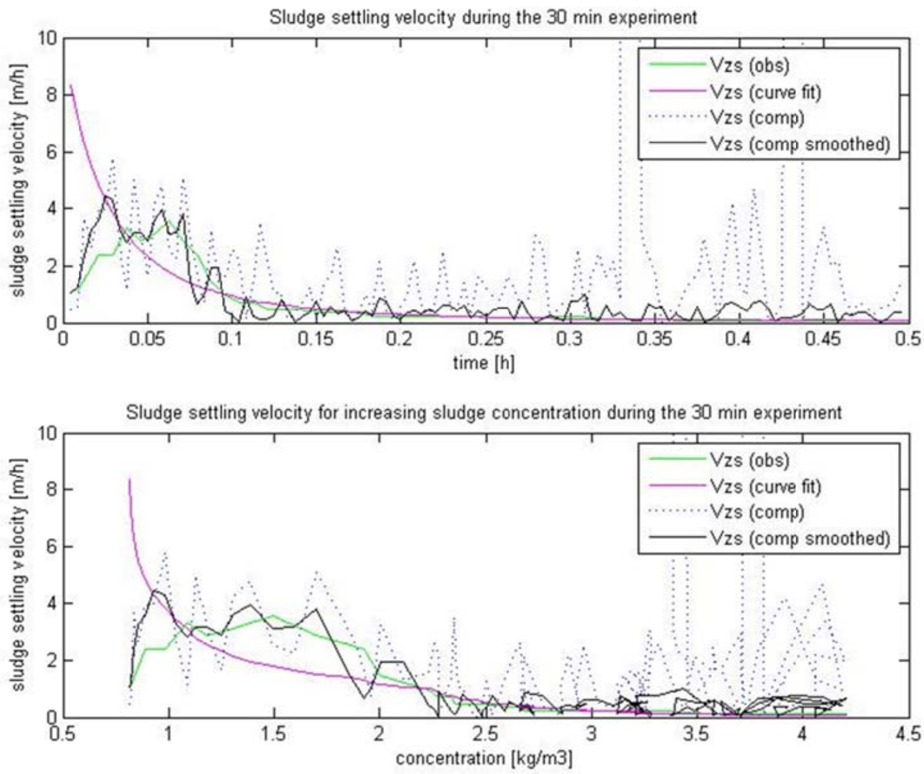

FIGURE 11 : TRACKED SLUDGE SETTLING VELOCITY DURING THE 30 MIN SETTLING EXPERIMENT AND DURING CHANGING CONCENTRATION CONDITIONS. SLUDGE TANK 2, CAMERA ON LADDER

Average computation time of the code is 96.43 seconds. Each time an input to the code is required the time measurement is interrupted. Thus the total computation time of the code is higher.

TABLE 6 : COMPUTATION TIME OF THE EXPERIMENTS CONDUCTED

Variable	Standard	Front flood light	Back flood light	Flash	Camera on table	Camera on ladder	Camera at 2.3 m, Zoom
Sludge Tank 1 EH	99.64	98.87	98.36	97.44			
Sludge Tank 2 EH	97.98				90.14	92.12	104.28
Sludge Urin Tank	97.93						
Sludge WWTP Winterthur	87.50						

5 Discussion

Although the method allows for the automated tracking of the sludge blanket during the 30 min sludge settling experiment, its sensitivity to the circumstancing conditions and to the different types of sludge cannot be neglected. Several issues such as the light conditions, incident angle of picture taking and variable sludge characteristics are detected. So far almost all the occurring tracking problems can be quantified and are assumed to be solvable which is discussed in the following.

The sludge from tank 1 from the Eawag experimental hall does not have a clear horizontal interface with the liquid above. Filamentous growth leads to a top layer where much more light than at the more compressed part passes. This leads to an underestimation of the sludge volume. When illuminated from the front, the color intensity of the sludge column is detected to be uniform by the camera. The lower concentration upper layer is detected as sludge as well, shifting the estimates into the confidence bounds of the observed data. The initial off set of the experiments with additional front illumination is probably due to the reflection of the sludge blanket in the top liquid layer just beneath the surface. This effect is always detected but direct light is raising the intensity of reflection. As soon as the sludge has settled enough, the reflection decreases and the actual sludge blanket is detected. Direct illumination of cylinders does not seem to be a good idea, although it can accurately detect the sludge blanket height after a certain set-off time. Flood light from behind the cylinders does not result in a better accuracy than the standard set-up without additional light, so the profit of this additional instrument is inexistent.

As expected, taking pictures from above underestimated the sludge volume whereas picture sequence taken from the bottom just in front of the cylinders overestimate the sludge volume. Knowing the geometry of the set-up, these scaling effects could be corrected. Scattering of estimates is caused by the sludge mirror seen from above. Changing threshold criteria probably could fix this problem.

The method fails when the total suspended solids in the liquor sample is low and no accurate threshold can be determined. The lowest possible concentration of sludge within the column still leading to accurate measurements is the one with a still identifiable solid – liquid interface which was not the case for the urine tank sample. The highest still possible sludge concentration has to have a substantial descent of the sludge blanket.

Only the estimates of the image sequences of the standard set up for sludge of tank 2 and for sludge from the WWTP Winterthur lie within the 95 % confidence interval. The tracking of sludge volume of sludge from the WWTP Winterthur has the lowest PBIAS which indicates best performance of the experiments conducted. Lying within the confidence bounds is true for the sludge from tank 2 and the position of the camera on the table and the horizontal camera distance of 2.3 m with a zoom as well. Latter is mainly due to the large confidence interval and applying zoom to large camera distances can be dismissed as a chance. The reliability of this statement is regarded critically as it is clearly possible that image distortion effects are influencing image processing remarkably, and the scaling due to distortion cannot be neglected. Taking the camera further away from the picture and applying a zoom results in a fuzzy image, but the sludge blanket is detected accurately except of three outliers probably representing flocks in the liquor sample column.

In general few outliers are detected. Few flocks were detected leading to outliers, but most of them can be detected as undesired effects of reflection. They are leading to an erroneous estimation of the percent bias which then seems to be inadequate to evaluate the model performance. It quantifies a general tendency of model performance which is not representative when having outliers in the data. Outliers are smoothed out before fitting a curve to it. Almost more accurate would be, not take them into account while fitting.

The curve fit is used to determine the critical time of hindered (zone) settling going over in compression settling. t_c together with the end of the lag stage can be used effectively to determine the v_{zs}. When t_c occurs settling velocity is fast and vice versa as t_c determines the cut of point taken into account for the determination of v_{zs}. Although t_c cannot always be determined accurately, the v_{zs} estimation is fairly well estimated for all the experiments. The settling velocity only depends on the shape of the settling process but not on the absolute values which means that scaling does not affect v_{zs}. Only consecutive outliers can lead to a wrong estimation of the hindered (zone) settling velocity (cf. Table 4). While t_c influences v_{zs}, the duration of the lag stage is determining the spacing between the 95 % confidence bonds. Having a long lag time results in a wider confidence interval (cf. Figure 8) which indicates the difficulty of implementation of the lag stage into the model.

Sludge volume index is calculated dividing the volume occupied by sludge after 30 min through the TSS measured in the lab. Sludge volume index determination depends therefore directly on the sludge volume estimation at the end of the experiment. Underestimation of sludge volume observation leads to a lower SVI while overestimation of sludge volume leads to a higher SVI. The percent bias is able to show these deviations when no consecutive off set is wrongly determined by the method. TSS measures based on the 100 ml filtered sample taken from the top layer of the liquor sample to represent the overall concentration is handled with caution. Although the 4 l liquor sample is stirred at 500 turns per minute, homogeneously mixing is never reached. A higher concentration of sludge at the bottom of the recipient is unavoidable with this measurement method. TSS measure is always underestimated leading to a higher SVI estimation. The SVI estimates are comparable to each other but their range has a set-off and are therefore only of importance at a relative scale.

The reliability of the exponential curve fit is regarded critically as it is only well adapted for sludge of fast dynamic settling curves, meaning settling goes through the different stages of Type III and Type IV settling. A maximum t_c threshold for exponential curve fit being reliable is set which operates quite well. When the threshold is exceeded, a linear function is more adequate to estimate the sludge volume. So far this diagnosis only is made but not jet applied in the computation method. Nevertheless it is already used to draw the confidence interval of 95 %. The SV of sludge from tank 2 settling is therefore an absolute estimate while the SV of the sludge from tank 1 can regarded critically only relative to the observed value.

The exponential curve fit switching to a polynomial of 1^{st} degree when t_c being high is adapted to the method. The optimal model structure is therefore depending on the settling behavior of the sludge blanket. Nevertheless the difficulty of accurately representing the start-up phenomena and the curvature where the neglected transition zone settling occurs are observed. Model function parameters are limited to two to allow for interpretation of the estimated parameters and making the model function simple enough for application in practice. The exponential model is sensitive to the initial guess. Depending on the initial guess different parameter sets are found and taking care of a good initial guess is crucial for the model performance.

Velocity tracking over the 30 min experiment in time and at increasing sludge concentration permits to evaluate the dynamics of the settling curve. The settling velocity of sludge form tank 1 is decreasing constantly with some local variations. The range of sludge concentration goes from 1 to 2.35 kg/m^3 which is quite small. The sludge is porous and does not settle very well which is confirmed by its high SVI associated to filamentous growth [10]. The dynamic settling behavior of sludge from tank 2 is clearly tracked by plotting the sludge settling velocity against time. Increasing sludge settling during the lag phase and maximum settling velocity at the hindered settling phase corresponding to v_{zs} is observed. Decreasing settling velocity during the short transition phase until a constant decrease of the final settling phase (compression settling phase) is observed. Looking at the settling velocity over the concentration range, same fast settling for low concentrations are observed. Concentration ranges are form 0.75 up to 4.15 kg/m^3 which is a fairly wide range. SVI of sludge in tank 2 is estimated to be around 100 ml/g which is considered as good settling sludge [10]. The same sludge concentration shows up to have different possible sludge settling velocities which is due to the scattering of the computed data points. The derivation of the fitted curve is not able to represent the changing dynamic behavior of the settling velocity, as the derivation of an exponential function is an exponential function. By smoothing out the estimates the velocity curve shape is similar to the observed velocity curve shape. Making valuable statements looking at the raw data is not possible, as the scattering of estimates leads to high differences in speed of settling. The concentration is probably underestimated as the initial TSS measurement is made for the top layer. Only the concentration range is reliable.

A time gain can clearly be reached using picture analysis since the SV estimation takes roughly 2 min instead of 30 min, needed by the conventional method. The additional benefit of this method is that the hindered sludge settling velocity can be determined in the same time as the SV, which was not possible with the conventional measurement method. The TSS measurement to estimate the SVI still has to be done in the laboratory and is not automatized yet.

6 CONCLUSION

The method of analyzing a line through the middle of the column based on the color channel intensities seems to be powerful to frequently evaluate the sludge volume and the hindered (zone) settling velocity. Nevertheless measurements by human operator cannot be disclaimed as scaling effects can occur. Regular calibration and verification of model performance is required.

Sensibility of the model to the initial parameter set and to the color channel intensity of the pixels along the line is elevated. Making a good first guess is crucial for the model performance. A first guess can be accurately done by analyzing sludge with similar settling behavior from another settling tank or made by involving an experimented WWTP collaborator. The line through the middle of the column should always be able to detect the pixel at the solids – liquid interface with lower intensity than the liquid above. Therefore no stuck particle neither reflection at the top layer of the liquid is allowed when accurate tracking of the interface is required. The glass cylinder should be washed after each experiment conducted to avoid particles sticking to the walls.

Standard procedure to estimate the Total Solids in a sludge – liquor sample is used and the calculation of SVI of observed and computed SV are comparable even though the sludge concentration was heterogeneous in the 4 l recipient. This could be observed as the final sludge blanket height of the 1 l column was always lower than half of the sludge blanket height of the 2 l column. This is due mainly to the filling up of the 1 l column with the sludge – liquor sample before the filling of the 2 l column. The concentration of sludge at the bottom of the 4 l recipient was higher and therefore the initial concentration of 2 l column as well. It would be interesting to know the influence of the smaller cylinder to the estimation to the SV as side effects may exist.

The standard set-up was useful to compare the different type of sludge. The sensibility of the method to the sludge characteristics and concentration could be evaluated. As it requires no laborious set up and no extra logistics, it represents an efficient set-up for image sequencing with a modern digital camera.

The best model performance is observed for the standard set-up with the sludge from the WWTP Winterthur and the set-up with the camera at 2.3 m from the column filled with sludge from tank 2. Good performance of the standard set-up was expected but the accurate performance of the model by sequencing fuzzy images is astonishing. It is difficult to accurately notice the sludge blanket on the image by the human eye. This has to do with the radial and tangential image distortion. Raising the distance from the camera to the column, the angles are reduced and the distortion effect is minimized. Although the images are fuzzy, the sludge blanket can be detected accurately with an adequate threshold. Image distortion can has an important influence to the accuracy of computed data and the option of undistorting images should be pursued for further detection of sludge – liquid interface by image analysis. But as computation time should be kept low and the benefit of undistorting each image may be low this option should be analyzed before taking it into application.

Another option to ameliorate the method and make it more robust consists in a multiline image analysis. Instead of one line through the glass cylinder, three to four lines may be analyzed vertically through the columns. The sensitivity of the method to small flocks can be minimized.

Overall it is clearly possible to track the sludge blanket during a 30 min settling experiment with an image processing tool such as Matlab. Deciding on a standard set-up the threshold deciding on the location of the sludge blanket can be set accurately. Whereas a manual is necessary when changing position of the camera and light conditions, fixing a standard set-up does not make the program inputs necessary anymore. When connecting the cylinder to the secondary clarifier, automation of backwashing of the cylinder and automatic registration of image sequences allows for complete independency of the measurement tacking process.

The method not only allows for SV measurement but also for the tracking of the solid – liquid interface and the evolution of the settling velocity. This consists in a big advantage toward the conventional method and allows for a frequent evaluation of secondary clarifier performance. An adequate functioning is assured.

REFERENCES

[1] AE Ozinsky and GA Ekama: Secondary settling tank modelling and design Part 1: Review of theoretic cal and practical developments, October 1995

[2] AE Ozinsky and GA Ekama: Secondary settling tank modeling and desing Part 2: Linking sludge settleability measures, October 1995

[3] Alexis Vanderhasselt, Peter A. Vanrolleghem: Estimation of sludge sedimentation parameters from single batch settling curves, April 1999

[4] Claudia Bänninger: Standardsarbeitsanweisung fr die Bestimmung des Schlammvolumenindex (SVI) in Belebtschlamm, Standard Operation Procedure (SOP) SVI 45-19, June 2006

[5] Daijun Zhang, Zhenliang Li, Peili Lu, Tian Zhang, Danyu Xu: A method for characterizing the complete settling process of activated sludge, May 2006

[6] Eberhard Morgenroth: Sedimentation, Process Engineering II, Lecture Notes, Spring Term 2013

[7] Karin Rottermann: Standardsarbeitsanweisung für die Bestimmung der Trockensubstanz (TS) und Glührückstand (GR) und Glühverlust GV in Schlämmen, Standard Operation Procedure (SOP) TS 45-16, July 2010

[8] Kris Villez: Image-based analysis of settling experiments (Documentation), April 2014

[9] Matlab R2010a Documentation, Version 2010

[10] Metcalf & Eddy: Wastewater Engineering; Treatment and Reuse, International Edition 2004, Fourth Edition

ANNEXE

TABLE 7: HANDBOOK

		15.05.2014		
Input	**Sludge Tank 1 Front Flood Light**	**Sludge Tank 1 Standard**	**Sludge Tank 1 Back Flood light**	**Sludge Tank 1 Flash**
Nb Exp	**1**	**2**	**3**	**4**
Column [l]	**2**	**2**	**2**	**2**
First Pic	**2780**	**2913**	**3040**	**3168**
Last Pic	**2899**	**3032**	**3159**	**3287**
Analised	**2800**	**3000**	**3041**	**3200**
BlueLine	**560**	**580**	**570**	**550**
Line	**650**	**620**	**620**	**600**
Code Specifcs				
n	**40**	**40**	**40**	**40**
top	**1**	**1**	**1**	**1**
bottom	**end**	**end**	**end**	
		20.05.2014		
Input	**Sludge Tank 2 Standard**	**Sludge Tank 2 Camera on table**	**Sludge Winter-thur Standard**	
Nb Exp	**1**	**2**	**3**	
Column [l]	**2**	**2**	**2**	
First Pic	**3293**	**3442**	**3592**	
Last Pic	**3412**	**3561**	**3711**	
Analised	**3333**	**3500**	**3600**	
BlueLine	**620**	**580**	**590**	
Line	**700**	**620**	**620**	
Code Specifics				
n	**40**	**40**	**40**	
top	**1**	**1**	**1**	
bottom	**end**	**end**	**end**	
		21.05.2014		
Input	**Sludge Urin Tank Standard**			
Nb Exp	**1**			
Column [l]	**2**			
First Pic	**3719**			
Last Pic	**3838**			
Analised	**3800**			
BlueLine	**580**			
Line	**620**			
Code Specifics				
n	**40**			
top	**1**			

bottom	end		

12.06.2014			
Input	Sludge Tank 2 Camera 2.3 m Zoom	Sludge Tank 2 Camera 2.3 m no Zoom	Sludge Tank 2 Camera on ladder
Nb Exp	1	2	3
Column [l]	2	2	2
First Pic	3874	4026	4285
Last Pic	3993	4145	4404
Analised	3900		4400
BlueLine	600		610
Line	620		570
Code Specifics			
n	40		40
top	1		3
bottom	2		end

TABLE 8: MATLAB CODE

```
clear all
close all
clc

tic
% % Analysis of manually aquired data
disp('Manually recorded data')
cd('..\LogBook');

yy='Year? ';y=input(yy);
mm='Month? ';m=input(mm);
dd='Day? ';d=input(dd);
sheep='Nb of experiment to analyze: ';sheet=input(sheep);
zweiodreis='2l or 1l experiment? ';ez=input(zweiodreis);
date=sprintf('%d-%02.0f-%02.0f', y, m, d);
hpic=0.5/120; % Convert 15s/pic to hours
if ez==1
    mml = 0.3390/1000; r = 0.031;
    else mml = 0.3985/2000; r = 0.04; % Convert ml of sludge column to m
end
excel=strcat(date,'.xlsx');
num=xlsread(excel,sheet);
nbpic=num(:,1)*hpic;
nbpicture=num(find(~isnan(num(:,6-ez))),1)*hpic;
head=num(find(~isnan(num(:,6-ez))),6-ez)*mml;

ftype = fittype('a*exp(b/(x+c))','coeff',{'a','b','c'}); % curve fit fct

title('Sludge settling curve (Excel)');hold on
fmes = fit(nbpicture,head,ftype,'StartPoint',[0.05, 0.3, 0.2]);
cofmes=coeffvalues(fmes);tcmes=cofmes(3);
[~,Imes] = min(abs(nbpicture-cofmes(3)));
[~,Tmes] = min(diff(head));
pmes = poly-
fit(nbpicture(Tmes:uint8(Imes/2)),head(Tmes:uint8(Imes/2)),1);Vmes=pmes(1);
pmes = poly-
```

```
fit(nbpicture(Tmes:uint8(Imes/2)),head(Tmes:uint8(Imes/2)),1);Vmes=pmes(1);
p1mes = polyval(pmes,nbpicture);
plot(fmes,nbpicture,head);hold on
plot(nbpicture, p1mes,'c-.'); ylim([0,max(head)])
xlabel('time [h]'), ylabel('sludge settling [m]');
legend('observed data','fitted curve','vsz');



% Analysis of pictures
fprintf('\nPicture analysis\n')
s='Number of first picture: ';begin=input(s);
e='Number of last picture (after 30 min): ';ending=input(e);
a='One pic analysis! Choice: ';pic=input(a);
folder=strcat('..\Bilder\',date);
cd(folder);
% Line selection (2^8 = 256)
jpgFilename = strcat('IMG_', num2str(pic), '.jpg');
ImgRGB = imread(jpgFilename);figure
imagesc(linspace(0,1944),linspace(0,2592),ImgRGB);hold on
lineblue='Vertical line through blue scotch: ';linetb=input(lineblue);
linemiddle='Vertical line through middle of column:
';middle=input(linemiddle);
plot([linetb,linetb],[1,2592],'Color','c','LineWidth',1)
plot([middle,middle],[1,2592],'c--','LineWidth',1)
title('Analyzed vertical Lines');
legend('Through blue scotch','Through the middle');
Line    =   squeeze(ImgRGB(:,middle,:)) ;
figure, hold on,
    plot(Line(:,1),'r-')
    plot(Line(:,2),'g-')
    plot(Line(:,3),'b-')
    xlabel('going down the column [nb of pixel]');ylabel('channel intensi-
ty');
    title('Color intensity through the middle of the column 2l')
figure; imagesc(linspace(0,1944),linspace(0,2592),ImgRGB);hold on
xlabel('nb of pixel');ylabel('nb of pixel');title('Bottom and Top of
Column');
Line    =   squeeze(ImgRGB(:,linetb,:));
blau=find(Line(:,3)>Line(:,1)&Line(:,3)>Line(:,2));
n=40; % nb of min consecutive values
% Bottom
bottom = [true;diff(blau(:))~=1 ];
s = cumsum(bottom); x =  histc(s,1:s(end));
idx = find(bottom);
out = blau(idx(x>=n));
bottom=out(end); % out(length(out));
plot([0,1944],[bottom,bottom],'k-.','LineWidth',1);
% Top
breit=x(find(x>=n));top=out(1)+breit(1);
plot([0,1944],[top,top],'k:','LineWidth',1);
legend('Bottom of column','Top of column');
% Calculation of nb pixel per ml
mlpix=2000/(bottom-top);

% Relative Procedure
jpgFilename1 = strcat('IMG_', num2str(begin), '.jpg'); % erstes bild
ImgRGB1=imread(jpgFilename1);
Line    =   squeeze(ImgRGB1(:,600,:));
ms =
mean((Line([top:bottom],1)+Line([top:bottom],2)+Line([top:bottom],3))/3);

poss=[];
```

```
for k=begin:ending;
    jpgFilename = strcat('IMG_', num2str(k), '.jpg');
    ImgRGB = imread(jpgFilename);
    Line    =   squeeze(ImgRGB(:,middle,:)) ;
    pix=(Line([top:bottom],1)+Line([top:bottom],2)+Line([top:bottom],3))/3;
    pos=find(pix<ms);
    pos=min(pos);
    if isempty(pos);
    pos=0;
    end
    pos=pos+top;
    poss=[poss,pos];
end
height=bottom*ones(1,length(poss))-poss;
volume=(height*mlpix*mml)'; volumehead=volume(find(~isnan(num(:,6-ez))),1);
volumesm=smooth(volume,'rlowess'); % smoothing by robust linear fit
figure
title('Sludge settling curve (MATLAB)');hold on
fcomp =
fit([1:length(volumesm)]'*hpic,volumesm,ftype,'StartPoint',[cofmes(1),cofme
s(2),cofmes(3)]);
cofcomp=coeffvalues(fcomp);tccomp=cofcomp(3);
[~,Icomp] = min(abs(nbpic-cofmes(3)));
[~,Tcomp] = min(diff(volumesm));
pcomp =
polyfit(nbpic(Tcomp:uint8(Icomp/2)),volumesm(Tcomp:uint8(Icomp/2)),1);Vcomp
=pcomp(1);
% pcompcorr = polyfit(nbpic((Tcomp-1):uint8(Icomp/2)),volumesm((Tcomp-
1):uint8(Icomp/2)),1);
p1comp = polyval(pcomp,nbpic);
% p1compcorr = polyval(pcompcorr,nbpic);
ppcomp = polyfit(nbpic(Icomp:end),volumesm(Icomp:end),1);
pp1comp = polyval(ppcomp,nbpic);
plot(nbpic,volume,'g.')
plot(fcomp,'m',nbpic,volumesm,'k.');hold on
plot(nbpic, p1comp,'c-.'); ylim([0,max(volumesm)]);
plot(nbpic, pp1comp,'c--'); % plot(nbpic,p1compcorr,'c:');
xlabel('time [h]'), ylabel('sludge settling [m]');
legend('raw data','smoothed data','fitted curve (sim)','vzs','vcs','vzs
(corrected)');
xlabel('time [h]'), ylabel('sludge settling [m]');
conc = ((num(2,8)-num(1,8))*10^-2)./(volumesm*pi*r^2); % g sluge in
100ml/m3
text((nbpic(end)/16),(head(end)/7),['X(0) = ',num2str(conc(1)),'
[kg/m3]']);

[d1,d2]=differentiate(fcomp,nbpic);
figure; subplot(2,1,1); plot(nbpic,d1); subplot(2,1,2); plot(nbpic,d2);

vsz1 = (volumesm(uint8(Icomp/2))-volumesm(Tcomp))/(nbpic(uint8(Icomp/2))-
nbpic(Tcomp))
vsz2 = pcomp(1) % = vsz1
v = abs(diff(volumesm))./diff(nbpic);
v_abl =
(cofcomp(1)*cofcomp(2))./(nbpic+cofcomp(3)).^2.*exp(cofcomp(2)/(nbpic+cofco
mp(3)))'; % = compr settling
figure; plot(nbpic(1:length(v)),v);hold on;plot(nbpic,v_abl,'k-
.');plot(nbpic,abs(d1),'k:');
xlabel('time [h]'), ylabel('sludge settling velocity [m/h]');

v_conc = cofcomp(2)*(mml*ez*1000)*conc(1)./((nbpic+cofcomp(3)).^2.*conc); %
=~d1 but with mass conservation
```

```
figure; plot(conc(1:length(v)),v);hold on;plot(conc,v_conc,'k*');

SV = fcomp(nbpic(end))/(mml*ez); % [ml/l]
TS = (num(2,8)-num(1,8))*10; % [g/l]
SVIcomp = SV/TS % [ml/g]
SVImes = (fmes(nbpic(end))/(mml*ez))/TS;

% Comarison of sludge settling curves
figure
hold on
plot(fmes,nbpicture,head,'g.');
plot(fcomp,'m',nbpic,volumesm,'k.');
plot(nbpic, p1comp,'c-.'); ylim([0,max(volumesm)]);
plot(nbpic, pp1comp,'c--'); % plot(nbpic,p1compcorr,'c:');
title('Comparison of sludge settling curves');
xlabel('time [h]'), ylabel('sludge settling [m]');
legend('observed data','fitted curve (obs)','simulated data','fitted curve
(sim)','vzs','vcs','vzs (corrected)');
text((nbpic(end)/16),(head(end)/7),['X(0) = ',num2str(conc(1)),'
[kg/m3]']);

% Visualization of the difference
figure
plot(nbpic,fcomp(nbpic)-fmes(nbpic));
title('Difference');legend('Computed - Observed');
xlabel('time [h]');ylabel('error (sludge settling [m])');
fprintf('\n'); toc

% 95 Confidence bounds
if tccomp <= 1
 papertype = fittype('a*exp(b/(x+c))','coeff',{'a','b','c'});
 cof = coeffvalues(fmes);
 conf = confint(fmes);
 deltaa=conf(2,1)-cof(1); deltab=conf(2,2)-cof(2); deltatc=conf(2,3)-
cof(3);
 delta=deltaa*exp(deltab./(nbpic+deltatc));
 plot(nbpicture,head,'*'); hold on;
 plot(nbpic,volume,'g+',...
    nbpic,papertype(cof(1),cof(2),cof(3),nbpic)+delta,'r:',...
    nbpic,papertype(cof(1),cof(2),cof(3),nbpic)-delta,'r:');
 ylim([0,0.45]);
 title('Confidence Intervals');xlabel('time [h]');ylabel('sludge settling
[m]');
 legend('observed data','raw data','bounds')
 text((nbpic(end)/16),(head(end)/7),['X(0) = ',num2str(conc(1)),'
[kg/m3]']);
else
 [pmes, ErrorEst]=polyfit(nbpicture,head,1);
 [p1mes, delta]=polyval(pmes,nbpicture,ErrorEst);
 plot(nbpic,volume,'g+'); hold on
 plot(nbpicture,head,'*',...
     nbpicture,p1mes+2*delta,'r:',...
     nbpicture,p1mes-2*delta,'r:');
 ylim([0,0.45]);
 title('Confidence Intervals');xlabel('time [h]');ylabel('sludge settling
[m]');
 legend('raw data','observed data','bounds')
 text((nbpic(end)/16),(head(end)/7),['X(0) = ',num2str(conc(1)),'
[kg/m3]']);
end


PBIAS = sum((head-volumehead)*100)/sum(head)
```

```
% Velocity analysis
concentration = conc(find(~isnan(num(:,4))),1);
subplot(2,1,1)
vmes = abs(diff(head))./diff(nbpicture);
[d1,d2]=differentiate(fcomp,nbpic);
vcomp = abs(diff(volume))./diff(nbpic);
vsm = abs(diff(smooth(volume,'rlowess')))./diff(nbpic);
plot(nbpicture(1:length(vmes)),vmes,'g') ;hold on; plot(nbpic,abs(d1),'m')
plot(nbpic(1:length(vcomp)),vcomp,'b:');plot(nbpic(1:length(vsm)),vsm,'k');
title('Sludge settling velocity during the 30 min experiment');
xlabel('time [h]'), ylabel('sludge settling velocity [m/h]');
legend('Vzs (obs)','Vzs (curve fit)','Vzs (comp)','Vzs (comp smoothed)')
ylim([0,3])

subplot(2,1,2)
plot(concentration(1:length(vmes)),vmes,'g'); hold on;
plot(conc,abs(d1),'m');
plot(conc(1:length(vcomp)),vcomp,'b:');plot(conc(1:length(vcomp)),vsm,'k');
title('Sludge settling velocity for increasing sludge concentration during
the 30 min experiment');
xlabel('concentration [kg/m3]'), ylabel('sludge settling velocity [m/h]');
legend('Vzs (obs)','Vzs (curve fit)','Vzs (comp)','Vzs (comp smoothed)')
ylim([0,3])
```

TABLE 9: RED / GREEN / BLUE CHANNEL ANALYSIS OF THE LINE THROUGH THE MIDDLE OF THE SLUDGE SETTLING COLUMN (FIRST LINE: SLUDGE TANK 1; STANDARD, FRONT FLOOD LIGHT, BACK FLOOD LIGHT, FLASH. SECOND LINE: SLUDGE TANK 2; STANDARD, CAMERA ON TABLE, CAMERA ON LADDER, CAMERA AT 2.3 M WITH ZOOM. THIRD LINE: STANDARD SETTING FOR SLUDGE WWTP WINTERTHUR, URIN TANK. LAST GRAPH: SLUDGE TANK 2; CAMERA AT 2.3 M WITHOUT ZOOM)

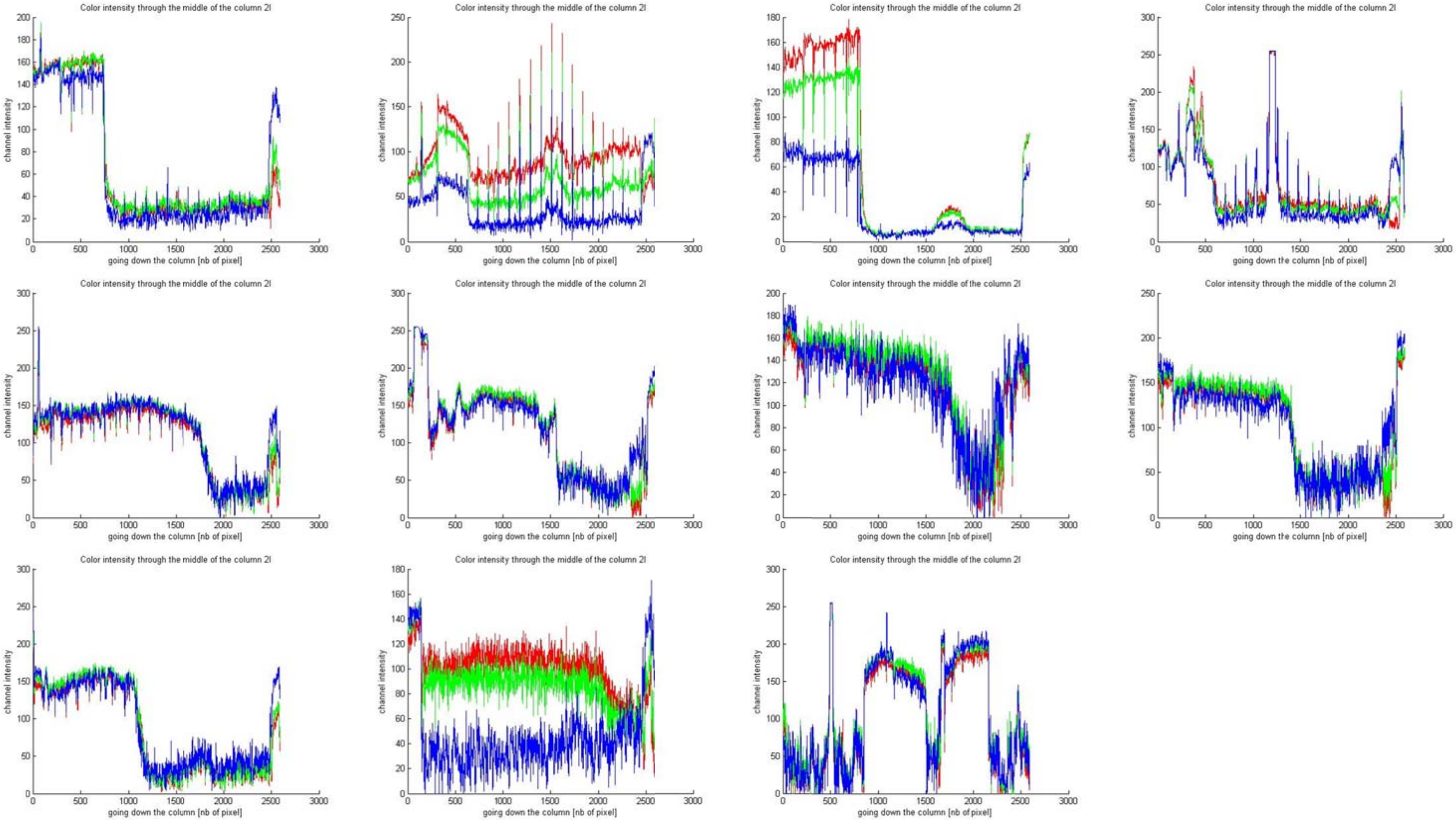

TABLE 10: OVERVIEW OF THE SIMULATION RESULTS COMPARED TO THE OBSERVED DATA COLUMN (FIRST LINE: SLUDGE TANK 1; STANDARD, FRONT FLOOD LIGHT, BACK FLOOD LIGHT, FLASH. SECOND LINE: SLUDGE TANK 2; STANDARD, CAMERA ON TABLE, CAMERA ON LADDER, CAMERA AT 2.3 M WITH ZOOM. THIRD LINE: STANDARD SETTING FOR SLUDGE WWTP WINTERTHUR, URIN TANK)

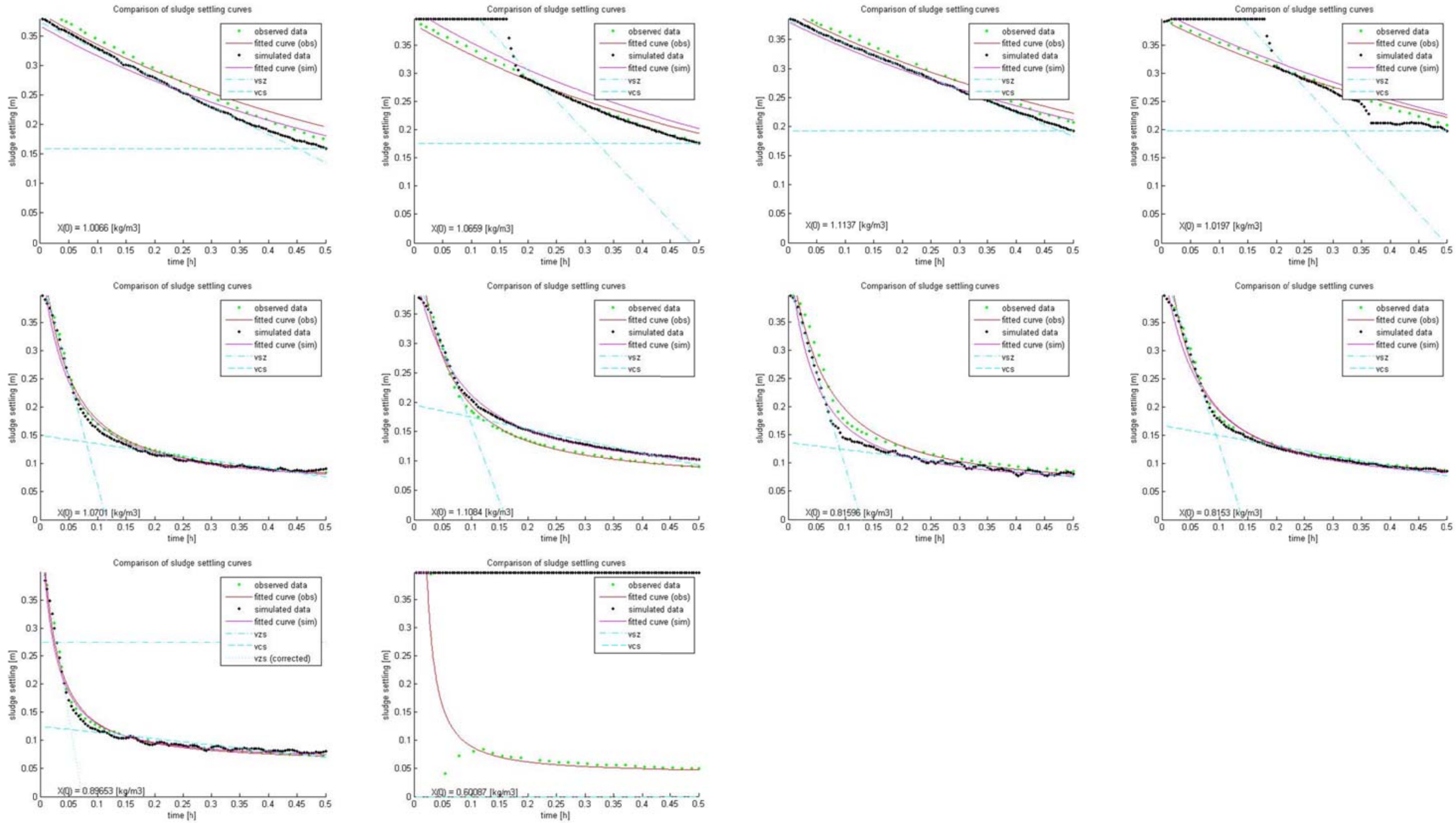

TABLE 11: OVERVIEW OF ACCURACY OF RAW DATA. 95% CONFIDENCE INTERVAL (FIRST LINE: SLUDGE TANK 1; STANDARD, FRONT FLOOD LIGHT, BACK FLOOD LIGHT, FLASH. SECOND LINE: SLUDGE TANK 2; STANDARD, CAMERA ON TABLE, CAMERA ON LADDER, CAMERA AT 2.3 M WITH ZOOM. THIRD LINE: STANDARD SETTING FOR SLUDGE WWTP WINTERTHUR, URIN TANK)