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AUTOMATED BATCH SETTLING COLUMN WITH VIBRATED RODS AND EVALUATION PROTOCOL FOR LIVING WATERS MUD THICKENING

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ABSTRACT

Gravity solid-liquid phase separation is applied in minerals industries, waste water treatment, filtration, sewage, drinking water, ocean (water) engineering, dredging, environment and biotechnology. The healthy nation of freshwaters like Lake Balaton and River Bodrog can be maintained by regular mud dredging. The on-water pure mechanical mud thickening would be a really beneficial technology. A new automated batch settling column with vibrated rods had been developed and fundamental tests had been carried out with model materials (glass sand) and muds (Siofok, Tihany, Tokaj). A numerical evaluation protocol with spline interpolation and derivation had been developed by with simple key parameters were determined. Results can be used for the design of a new type of thickener called the rod-lamella thickener.

Keywords: Batch settling test (BST), free - hindered and zone settling, mud thickening, tank - lamella and vibrated rod thickener.

1. INTRODUCTION, AIM AND LITERATURE SUMMARY

Gravity sedimentation is the most common technique applied for solid-liquid separation, and batch settling tests (BSTs) are generally used to obtain detailed information of sedimentation behaviour of suspensions. Before sizing thickeners and clarifiers for many different professional areas BSTs are performed. Different areas can be mentioned, such as minerals industries, waste water treatment, filtration, sewage, drinking water, ocean (water) engineering, dredging, environment and biotechnology [1]. Dredging of the accumulated mud from living waters in Hungary, - especially from Lake Balaton and Rivers Tisza and Bodrog – is really important for keeping the healthy nature of these waters. In the mentioned professional areas, the thickening of suspensions containing very fine particles is often solved by using different chemical or organic additives as flocculants. These are fairly expensive processes and the usage of these materials for mud thickening might cause environmental problems for the nature. Our exclusive aim was the development of pure mechanic equipment and technology by with the hydraulically dredged mud from living waters can be processed on the water on the hydraulic dredging ship. Dredged sand should be separated and carried back to the water and only the thickened mud should be transported out to the bank. If water content of the thickened mud is low enough that even makes some kind of mud utilization to be possible. This paper reports about the preliminary scientific work, done before the development of the rod-lamella thickener. A new automated batch settling column (45 dm^3) was developed. The height of the settling pulp was measured by an optical system. The column was equipped with an interchangeable rod system submerged into the pulp. Rods could be vibrated by a linear motor and this way almost any motion function of different vibrations could be set, depending on the programming of the linear motor. A model material, namely fine glass sand from Fehérvárcsúrgó, Hungary and mud samples from Lake Balaton and River Bodrog were used for sedimentation testing. A numerical evaluation method using National Instruments LabWindows C++ software with the SpInterp spline function was developed. By this software the first (velocity) and second (acceleration) derivatives of the spline smoothed settling curve (height of the settling mud as function of time) and the main technical parameters for thickener design can be determined. Theoretical terminal settling velocity calculations were carried out by methods developed earlier [8, 9, 10]. The aim of the carried out research work was to reveal consequences necessary for the rod-lamella thickener development.

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In a comprehensive study in 1993 Concha and Barrientos [2] revised the existing gravity thickener design methods. Three types of design methods were listed. Methods based on macroscopic balances (Coe and Clevenger, Mishler), those based on kinematic models (Kynch, Talmage and Fitch, Oltmann, Yoshioka-Hasset, Wilhelm and Naide) and those based on dynamic models (Concha and Bustos, Adorjan, Michaels and Bolger, Robert). According to the macroscopic balances models [3] four discrete zones can be distinguished in industrial thickeners (settling tanks) as well as in batch settling columns. At the top, there is a zone of clarified liquid labelled zone I. If bad thickener operation happens this zone might be turbid because of un-thickened solids, this case is called the thickener overflow. Beneath the clarified liquid is zone II, called the hindered settling zone. Zone II contains pulp of uniform concentration settling at a constant rate. If the concentration is high enough, because of particle – particle interactions, the higher terminal settling velocity particles are not able to settle with this high speed, therefore all the particles are forced to settle together. If there are too many cars in a highway, all the cars must go with the same speed. The situation is similar here. The actual concentration of zone II primarily depends on the solids mass feed rate of the thickener. If the solids feed rate exceeds a maximum the height of zone I bottom is decreasing and the thickener soon starts to overflow. Below zone II a transitional layer, namely zone III might be evaluating. Below zone III the so called compression zone (IV) containing a thick pulp or sediment is situated. The transitional zone (III) does not evolve at all the cases but it separates the above settling zones (region) from the below consolidating zones (region). The solids concentration in the transitional zone sharply increases from the evolved concentration of hindered settling into the much higher concentration of the settled consolidating or compressing solids in zone IV. The concentration in zone IV is further increasing vertically downwards up to the lower discharge point reaching the thickened slurry concentration of the product of the thickener. The kinematic thickener design models are generally based on Kynch's theory about the sedimentation velocity, that at any point in the suspension it is only a function of the local particle concentration. It is evidently valid only in zone II; therefore dynamic design methods had been developed. The consolidation of the sediment under its own weight involves forces not taken into account in the kinematic theory, especially when flocculants are used. Dynamic models take into account compressibility features of the settled solids. Garmsir and Haji Amin Shirazi [1] carried out 300 batch settling tests and compared many equations and methods for the evaluation of tests and for the determination of key parameters for the thickener design. They suggested the calculation of the so called I index determined on the basis of certain parameters of the settling curve for the easy comparison of different settling behaviour of different materials and flocculants. Balbierz and Rucka [4] presented the results of a series of batch settling column tests conducted on sludge from pilot-scale two-stage de-ammonification treatment facility. They compared the well-known settling models and equations of Vesilind, Takacs et al. and Liu et al. for their tests. They concluded that the batch settling tests allowed for a proper characterization of sludge settling properties and the Takacs sedimentation model provided a good prediction of sludge settling behaviour, if the sludge had a flocculent-like nature. Elena Torfs et al. [5] published a practical guide for precise execution of batch settling tests especially for wastewater treatment applications. The usage and determination of the so called stirred specific volume index (SSVI3.5) and the hindered settling velocity were presented. Stirring a sample during settling reduces wall effects, short circuits bridge formation effects, thereby creates conditions more closely related to real sludge behaviour. Lately numerical simulation techniques have arrived on board of this field too. Xu et al. [6] employed the coupled CFD–DEM (Computational Fluid Dynamics – Discrete Element Method) method to simulate the sedimentation process. Such wide range of solid concentration (0.05~0.6 m/m) was simulated. The fluid phase was solved in the CFD program by the locally-averaged incompressible Navier–Stokes equations and particles' motions were tracked in the DEM module based on Newton's second law of motion. The contact force exerted on every particle due to the fluid–particle interactions and collisions between particles and particle-wall collisions during the settling was simulated.

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2. MATERIALS AND METHODS

2.1. Materials

A model material and real living water muds had been selected for the investigation. The model material should be inert, very fine granular and easily reproducible. The selected material was processed glass sand from Fehérvárcsúrgó, Hungary from a glass mineral mine processing plant. Two dry samples - of about 100 kg each - were taken labelled GS30 and GS75. 30 and 75 indicates the name of product of the processing plant, namely 90 % is smaller than 30 or 75 μm. The removal of the accumulated mud is especially important for the Lake Balaton and the River Bodrog, both are situated in Hungary. Higher quantities of samples (about 600 l thickened suspension from each) had been taken from the north and south part of the Lake Balaton (Tihany and Siófok) and the River Bodrog in Tokaj labelled as Tihany, Siofok and Tokaj samples. After appropriate sample processing many subsamples were produced for fundamental material testing and for later technological investigation. Particle size distribution was measured by wet hand sieving with a standard 400 mm laboratory sieve series above 45 μm and below this size a Horiba LA950-V2 laser particle sizer was used. Figure 1 shows measured particle size – distribution (PSD) curves of the samples.

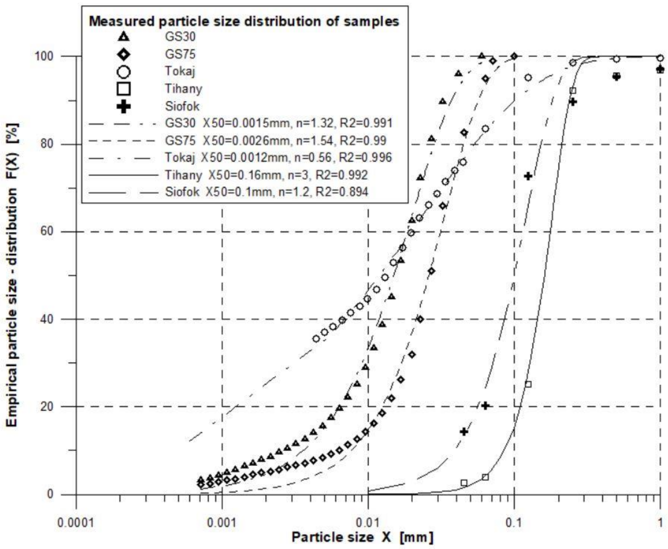

Figure 1. Measured PSD curves of the samples.

The well-known Rosin-Rammler (RR) function: $F(X)=1-\exp\{-\ln2((X/X50)^n\}$ was curve fitted. Despite of the fact that the Coefficient of Determination (R^2) values are really high and that indicates good fit in a mathematical sense, but clearly visible to the naked eye that the RR curves do not fit well into the very fine and very coarse particle size regions. The Tihany sample had the narrowest (n=3) and the Tokaj sample had the widest (n=0.56) PSD. The Tokaj sample contained the highest amount of fine particles, namely 37 % was still finer than 5 μm. The particle density (ρ_s) was measured in a 500 cm^3 laboratory pycnometer in either denaturised alcohol or distilled water. All tests had been repeated four times; only the averages are shown here. The glass sand samples could be treated as a one-component material; therefore carefully splitted subsamples were tested only. In contrast the particle density of each sieved discrete particle size fraction of the mud samples had been tested. Table 1 shows the measured particle density values.

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Table 1. The measured particle densities of samples.

GS30	GS75	Particle size fraction	Tokaj	Tihany	Siofok
kg/m^3	kg/m^3		kg/m^3	kg/m^3	kg/m^3
2530	2532	0-45 μm	2171	1901	2162
		45-63 μm	2263	2693	2585
		63-125 μm	2442	2662	2607
		125-250 μm	2421	2625	2483
		250-500 μm	2014	2552	2510

The particle density and size distribution of mud samples give some clues about what materials were contained. The finest granular material was the Tokaj sample, and the lower densities of the fine size fractions indicate clay minerals. The intermediate size fractions of the Tihany and Siofok samples were mainly sand, but the measured low particle density values of the fine and coarse size fractions indicate either $CaCO_3$ or some organic materials. Particle shape of each size fraction was tested in an optical microscope (Zeiss AxioCam). Figure 2 shows two characterising photos about the particles.

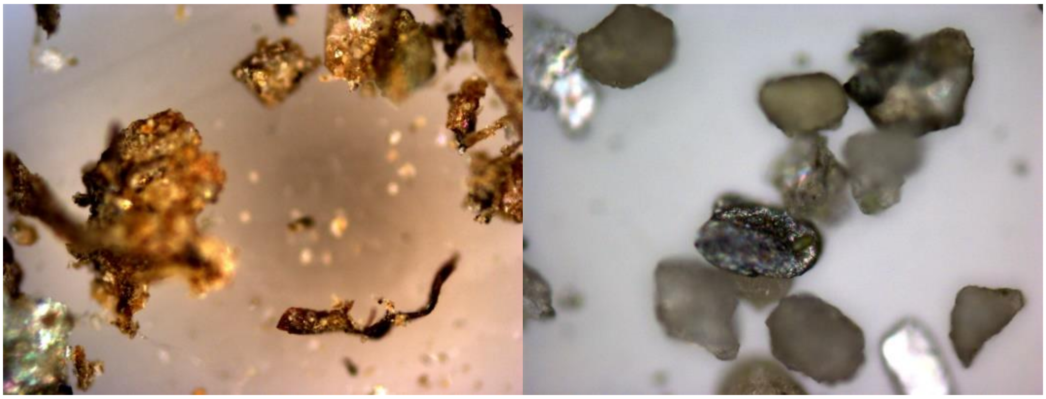

Figure 2. Tokaj sample (left, 100 times magnification) and Siofok sample (right, 200 times magnification).

2.2. Methods

2.2.1. Experimental equipment

A standard plexiglass settling column (height: 33.3 cm, diameter 8.8 cm, volume 2 litres) was used for the preliminary tests. Four 1 cm diameter and 32 cm length rods were mounted on a vibrator and were submerged onto the settling column. The rods could be vibrated by a fixed 50 Hz frequency and the amplitude of the sinusoidal vibration could be set to be 1, 1.2 and 1.4 mm. The applied vibrations are marked V0 (no-vibration), V1 (50 Hz-1 mm), V2 (50 Hz-1.2 mm) and V3 (50 Hz-1.4 mm) here. A new pilot scale automated settling column with vibrated rods had also been developed. Schematic drawing and pictures of it is shown in Figure 3.

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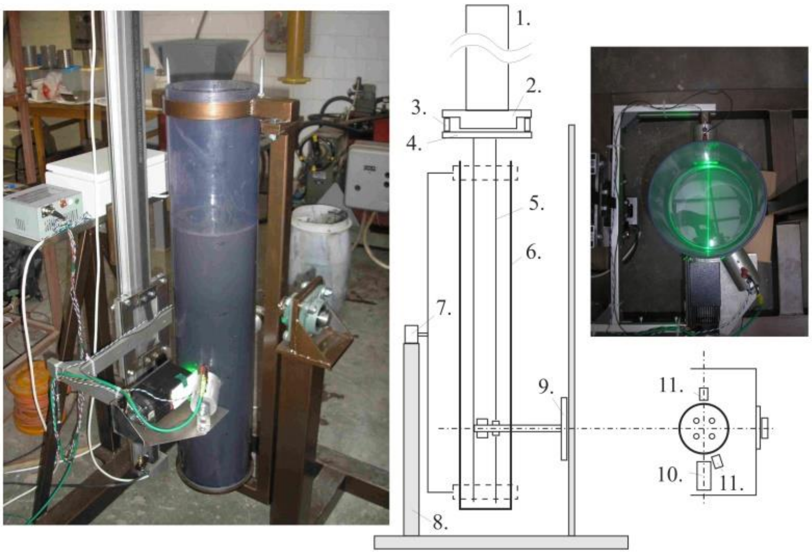

1. Traversing system to uplift the rod structure.
2. Electromagnetic part of the linear motor.
3. Bearing, gap is 0.9 mm.
4. Permanent magnet part of the linear motor.
5. Rod structure.
6. Settling column made by transparent material.
7. Bearing to revolve the settling column.
8. Base frame.
9. Traversing system for the up and down moving of the light sensor.
10. 350 mW laser.
11. Light sensors.

Figure 3. Schematic drawing and photo about the automated settling column.

The settling column was made by transparent plastic material (plexiglass). The diameter of it was 24 cm and the height was 100 cm. Useful volume of it was about 45 l. The manual feed, emptying and mixing in this large size tank compared to normal batch settling columns was difficult, therefore, the tank was mounted on a steel fork and the middle of this fork was mounted on bearing. By this way the tank could be turned around the bearing. To measure the height of the settling pulp and the average solids concentration at a given height an optical system was installed comprising a 350 mW green laser diode and two light sensors. A computer controlled traversing system was also built to move the optical system up and down along the vertical axis of the column. The light sensor installed at the opposite side was calibrated to measure solids volumetric concentration. Unfortunately, at higher concentrations no any light could go through the suspension, therefore this sensor was usable only for lower than about 2 V/V % concentrations. Another light sensor was installed to sense backscattered light. The height of the settling pulp could be exactly measured by this sensor because there was a significant backscattered light intensity drop at moving downward from the clarified zone I into the hindered settling zone II. This pilot scale settling column was equipped with a vibrated rod system comprising a linear motor mounted on another traversing mechanism. Different rods could be mounted onto the moving magnet part of the linear motor and the rods and the linear motor altogether could be lifted up by the traversing mechanism during the feed of the settling column. The resolution of the linear motor was 0.01 μm. Parameters (frequency, amplitude) and the motion function as well of the vibration was just matter of programming of the linear motor to be set. The data acquisition and control software of the automated settling column was written in C++ in LabWindows CVI.

2.2.1. Evaluation protocol

The result of a batch settling test (BST) is the measured H-t (height of the settling pulp versus time) point pairs. Physical parameters of the solids and liquid in the column can also be measured. Csőke et al. [7] applied the curve fitting of the well-known concatenated sections cubic spline function (Equation 1) into the measured H-t points as the first step of the evaluation protocol.

$$y = a_3 \cdot x^3 + a_2 \cdot x^2 + a_1 \cdot x + a_0 \quad (1)$$

This numerical mathematical method was replicated here. The evaluation software had been written in National Instruments: LabWindows CVI, C++ language using the "Spline" and "SpInterp" functions. Figures 4 and 5a show some measured settling curves (H/H_0-t) as examples. H_0 is the loaded height and C_0 is the initial volumetric concentration of the suspension in the column. The no-vibration (V0) curves follow the well-known shape and the zones described earlier can be well identified. The interpolated spline function goes through all the measured points. The first (v - velocity) and the second (a - acceleration) derivatives as continuous functions can be calculated as function of the settling time. A quick change of the derivatives (non-smooth function) indicate non-perfect measurement points. By this way the measured results can be checked and corrected. Among others, Figure 5a shows the settling curve of the 0.2 initial volumetric concentration (volume of solids over volume of suspension) no-vibration (V0) Siofok mud. The hindered settling zone, where the H/H_0-t function is linear according to the Kynch kinematic theory can be well seen. Just looking at Figure 5a this function seems to be linear on that zone, but Figure 5b shows its first derivative, namely the velocity of settling or compressing. According to Figure 5b the measured hindered settling velocity (v_H) is not constant here, because the interpolated spline function follows precisely the measured points, and there are always some minor measurement errors. This indicates how powerful this numerical method is. By this spline interpolation technique new points can also be generated. And most importantly this numerical method can be applied for both the kinematic and dynamic thickener models, because derivatives of the complete settling curve can be determined. The volumetric concentration of the pulp (C_z - suspension below the visible boundary layer) can be calculated by Equation 2left, according to the Kynch theory. This concentration is determined by another way and it is called as "dilution".

$$C_z = \frac{H_0 \cdot C_0}{H + v \cdot t} \qquad D = \frac{1 - C_z}{\rho_S \cdot C_z} \qquad S = \rho_s \cdot C_z \cdot v \tag{2}$$

The dilution is the volume of the liquid phase over the mass of the solids phase. The dilution (D) can be calculated by Equation 2middle and the so called solids flux (S) by Equation 2right. Figure 6a shows measured solids flux versus time curves of Siofok mud samples and Figure 6b shows the dilution and the integral of dilution versus time curves of Siofok mud samples. The presented method and the obtained curves can be utilised for later thickener design, however the aim of this study is the investigation of the effect of vibration into settling; therefore, simple characterising numbers were needed. The so called hindered settling velocity was determined as the average velocity of the hindered settling zone (linear range of H/H_0-t). See Figure 5b. The maximum solids flux was determined as the maximal value of the solids flux – time curve. These two values characterise the settling region of BSTs. The compression region was characterised by the volumetric concentration of the settled and compressed solids. This parameter was simply calculated on the basis of the height of the solids on the bottom of the column after a longer time period. Vibration really affected the concentration of the settled solids.

3. RESULTS AND DISCUSSION

Fundamental tests with the selected model material, namely with glass sand were carried out. Figure 4 shows the measured H/H_0-t points and the fitted spline functions of the GS30 samples, when the initial suspension volumetric concentration was set to be 0.1 as an example.

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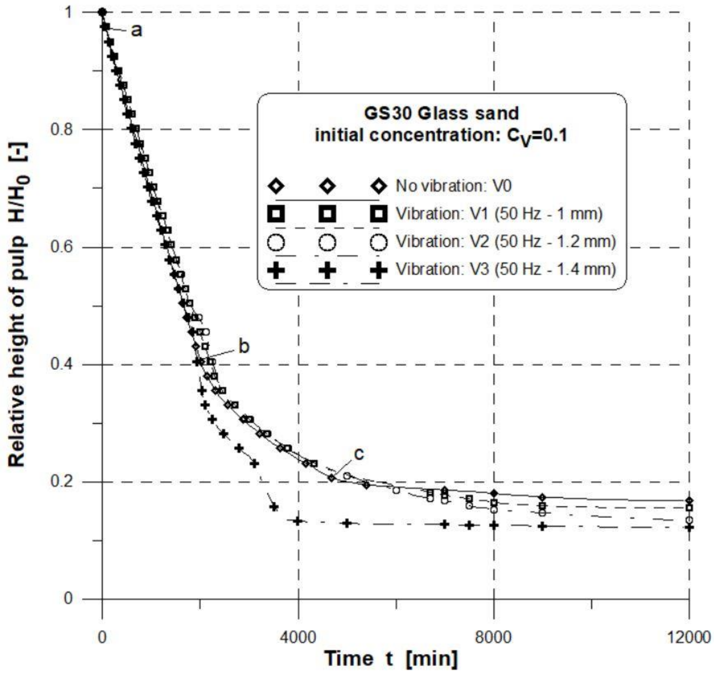

Figure 4. Settling curves of GS30 glass sand as function of vibration.

The no-vibration (V0) settling curve follows the well-known shape described in the literature [5]. After a very short lag phase at point (a) zone (hindered) settling with a constant speed of pulp boundary decreasing starts and then lasts until point (b). The transition phase starts at point (b) when the sludge blanket reaches the transition layer. The last phase called compression starts at point (c). Looking at Figure 4 many conclusions can be drawn about the effect of vibration into settling. First of all the settling curve of the most intense vibration (V3) is significantly different in the compression BST region. It is obvious that granular materials can be compressed by vibration. A mason in the construction industry generally compacts concrete with vibration. The result of the vibration is a much higher solids concentration. On the other hand compaction starts to happen earlier too; therefore the shape of the settling curve is different. It is also interesting that in this case vibration almost does not affect settling speed in the settling BST region. The linear height – time phase (hindered settling phase) of all of the vibration settling curves is clearly visible and there is only a very slight difference on the slope as function of the vibration amplitude. The developed spline smoothing technique can efficiently be used for all the curves because this function goes through all the points and its derivatives show immediately any un-smoothness of them. Table 2 shows the measured settling parameters of the GS30 glass sand sample BSTs.

Table 2. Measured settling parameters of model material (GS30) tests.
(Measured in the standard 8.8 cm diameter plexiglass settling column.)

Sample	Initial volumetric concentration [-]	Vibration	Hindered settling velocity [mm/min]	Maximum solids flux [kg/m^{2}h]	Volumetric concentration of settled solids [-]
GS30	0.1	V0	0.1	1.8	0.61
GS30	0.1	V1	0.095	1.5	0.64
GS30	0.1	V2	0.09	1.6	0.73
GS30	0.1	V3	0.15	1.9	0.81
GS30	0.2	V0	0.025	1.1	0.46

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GS30	0.2	V1	0.025	1.2	0.6
GS30	0.2	V2	0.027	1.5	0.86
GS30	0.2	V3	0.025	1.2	0.86
GS30	0.3	V0	0.0095	0.9	0.52
GS30	0.3	V1	0.011	1.0	0.55
GS30	0.3	V2	0.014	1.3	0.62
GS30	0.3	V3	0.011	1.1	0.66

The initial concentration does really affect the settling behaviour of the glass sand suspensions. Higher initial concentration results lower hindered settling velocity and lower maximum solids flux. It is obvious because higher concentration results higher rate of hindering among the particles. The hindered settling velocity and maximum solids flux are features of the settling BST region. These values are pretty similar for a given initial concentration independently from the vibration; so data in Table 2 also indicates that for this material vibration almost does not affect settling in the settling BST region. The volumetric concentration of settled solids is the feature used for the characterisation of the compression BST region. Higher vibration amplitude results higher final concentration on the tested range. The maximum final volumetric concentration is 0.86 and that is a really high number. It depends on the particle size and shape distributions of the solids, namely how the vibration can compress the particles. Because of the vibration particles can have better and better orientation; therefore more tight space filling is the result. The free settled volumetric solids concentration is about 0.52 – 0.61 without vibration and vibration can significantly increase it up to 0.86. Table 3 shows the measured settling parameters of the GS75 glass sand sample BSTs.

Table 3. Measured settling parameters of model material (GS75) tests. (Measured in the standard 8.8 cm diameter plexiglass settling column.)

Sample	Initial volumetric concentration [-]	Vibration	Hindered settling velocity [mm/min]	Maximum solids flux [kg/m^{2}h]	Volumetric concentration of settled solids [-]
GS75	0.1	V0	0.162	3.4	0.54
GS75	0.1	V1	0.145	2.5	0.57
GS75	0.1	V2	0.142	2.9	0.65
GS75	0.1	V3	0.14	3.8	0.75
GS75	0.2	V0	0.06	2.44	0.44
GS75	0.2	V1	0.055	3.5	0.56
GS75	0.2	V2	0.055	4.2	0.7
GS75	0.2	V3	0.055	3.2	0.85
GS75	0.3	V0	0.02	1.4	0.52
GS75	0.3	V1	0.022	2.28	0.56
GS75	0.3	V2	0.023	1.8	0.59
GS75	0.3	V3	0.025	1.5	0.62

The only difference between GS30 and GS75 is the particle size range, GS75 is coarser a little. Therefore the hindered settling velocity and maximum solids flux values are higher but the observed tendencies in the settling BST region are the same. The tendencies are similar in the compression BST region also, final free settling volumetric solids concentration without vibration is about 0.44 – 0.54 and the maximum measured vibrated final volumetric concentration is 0.85.

The effect of vibration on the settling behaviour of real living water muds had also been tested. The settling curves of the Siofok samples are shown on Figures 5 and 6.

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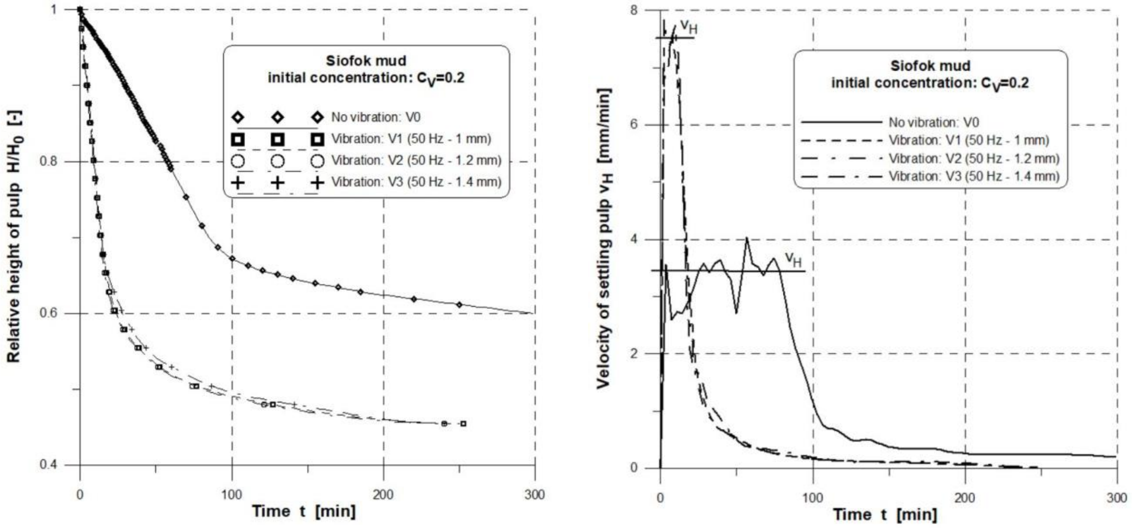

Figure 5. Settling curves of Siofok mud as function of vibration.
Fig. 5a. Relative height of pulp versus time (left), Fig. 5b. Velocity of settling pulp versus time (right).

The no-vibration - Siofok mud - initial volumetric concentration 0.2 BST curve was measured in the 24 cm diameter automated settling column, while the vibrated curves were measured in the 8.8 cm diameter traditional one. Therefore, the visible big difference might be result of the vibration or the size of the column. Unfortunately, there are no more measured data yet, so there is no answer to this question, namely which of them is the reason of this visible big difference. Figure 5b shows how the hindered settling velocity was determined. Because the quantitative value of this velocity will not be used for process engineering design, therefore this value was simply read as the average value of the v-t plot of linear (hindered) settling zone and statistical evaluation has not been performed.

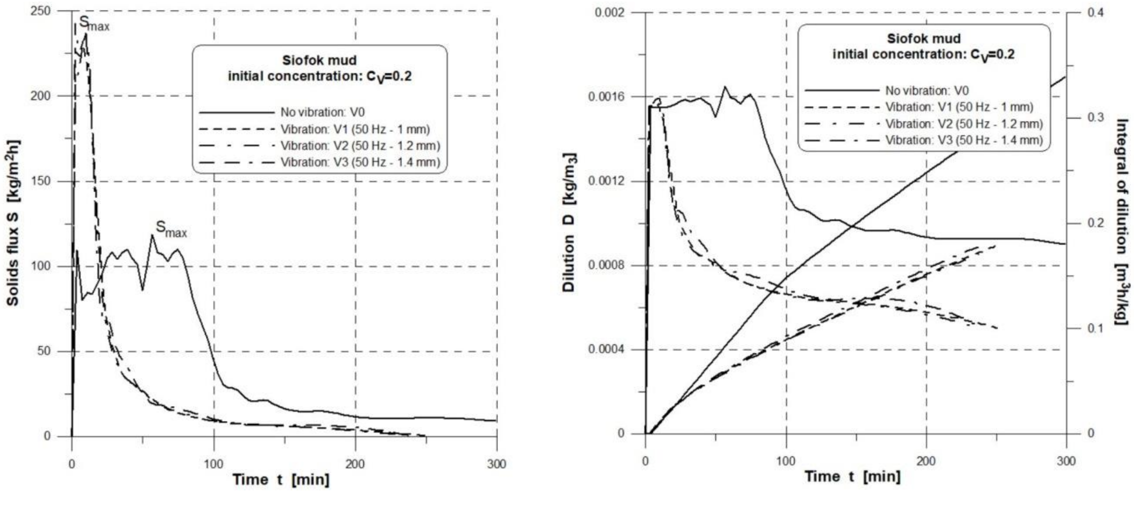

Figure 6. Settling curves of Siofok mud as function of vibration.
Fig. 6a. Solids flux versus time (left), Fig. 6b. Dilution and integral of dilution versus time (right).

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Table 4 summarises the measured data of living water muds BST tests.

Table 4. Measured settling parameters of mud tests.
(Vibrations were measured in the standard plexiglass settling column, others were measured in the automated settling column.)

Sample	Initial volumetric concentration [-]	Vibration	Hindered settling velocity [mm/min]	Maximum solids flux [kg/m^{2}h]	Volumetric concentration of settled solids [-]
Tokaj	0.1	V0	0.8	9.94	0.189
Tokaj	0.2	V0	0.012	0.43	0.22
Siofok	0.1	V0	14.41	230	0.35
Siofok	0.2	V0	3.5	119	0.38
Siofok	0.2	V1	7.57	232	0.44
Siofok	0.2	V2	7.87	243	0.44
Siofok	0.2	V3	7.73	234	0.44
Siofok	0.3	V0	2.7	116	0.45
Tihany	0.1	V0	11.62	256	0.41
Tihany	0.2	V0	4.3	153	0.39
Tihany	0.3	V0	1.9	91	0.41

Real mud BST data also indicates that vibration slightly affects slurry thickening on the settling region, but it affects thickening very significantly on the compression region. On the settling region particles or particle flocs are still moving downward. Vibration might induce many different effects, and many of them might slow down and many others might speed up the downward particle movement. If vibration is too intensive the result might be mixing instead of thickening. Intense vibration might break down the formed flocs and therefore settling speed of the individual particles will be lower. A moderate amount of energy input might decrease the hydrodynamic drag around the particles and might decrease particle – wall interactions, therefore settling speed might increase. While higher energy input might result in sufficient kinematic energy for the particles to be mixed. The described tests are not suitable to answer these fundamental questions, but consequences can be drawn for the design of a new type of mud thickener. The new thickener should be comprised of two parts. A pre-thickening part is necessary where the settling region of thickening is carried out. The pre-thickening part might be a lamella thickener. The compression of the pre-thickened slurry might be carried out in the second machine part where vibrated rods are used to intensify compression. This is the operating principle of the so-called rod-lamella thickener.

4. CONCLUSIONS

Special batch settling tests had been carried out in a traditional and in the newly developed automated settling columns, where vibrated rods were submerged onto the settling suspension. The developed spline interpolation and derivation test evaluation protocol was proved to be an effective method for both the traditional and the vibrated BSTs. Simple features: the hindered settling velocity, the maximum solids flux and the volumetric concentration of the settled and compressed solids were determined for all the tests. Conclusions can be drawn on the basis of these features. Vibration only slightly affected the thickening in the settling BST region while vibration strongly affected it in the compression BST region. The settling curve of a vibrated BST looks totally different, but the developed spline interpolation technique can be effectively used for the evaluation. Conclusions can be used for the design of the rod-lamella thickener, namely a pre-thickening unit is necessary for the settling region and in the post-thickening unit vibrated rods can be used for the compression.

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