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COMPARISON OF FOUR PARTICLE DEPOSITION RATE FORMULAE IN LAMINAR FLOW

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ABSTRACT: This research aimed to obtain the deposition rate in laminar flow for sediment traps. There are two essential variables related to the performance of the sediment traps for irrigation systems, namely the deposition rate and the efficiency of flushing. This research examines the rate of sediment deposition in laminar flow in a sediment trap. The fall velocity is a fundamental parameter in the modeling and interpretation of the deposition rate. As a rice-producing country, paddy fields with irrigation are many in Indonesia. The case study in this research is on the Macan weir in Subang district - West Java. The data of sediment properties in the Macan river obtained by field investigation from August to December 2019 are sediment concentration, water temperature, grain particle gradation, and the maximum discharge that enters the intake gate. The sediment transport rate that passes through this Macan weir was calculating in 2020. Non-cohesive type of sediment to be an exam in this study. A limitation of the sediment gradation to be captured >0.06cm and neglect <0.06cm and allowed to enter the irrigation system. The method of this research, to determining the sedimentation rate through various literature and formulae methods. Comparing deposition rates are the Stokes-Newton, Farag, Fergusson-Church, and Dietrich law equations. Compare it visually with the plots of equations for laminar conditions of non-cohesive sediment settling in the water at 20°C. As the first step in further research, the result is to determine the appropriate equation for the case that applies to this study.

Keywords: Sediment, Non-Cohesive, Deposition, Laminar, Desilting basins, Sediment traps

1. INTRODUCTION

Indonesia has high rainfall intensity and has many rivers with various characteristics, geographical conditions with a steep slope. It was making the potential for sedimentation carried through the river in the head structure of the irrigation system. In an irrigation scheme, there is the head structure, namely the weir. Nowadays, the sediment traps as part of the weir to ensure non-cohesive sediment do not enter the irrigation scheme and reduce the irrigation canal wet perimeter section. Sedimentation is one of the operations to separate a mixture of solids and liquids (slurry) into a clear liquid and sludge (slurry with a dense concentration). Sedimentation is a method of separating solids and liquids using the force of gravity. The dropping of transported materials (sediments), or the process by which transported materials are left in new locations, is called deposition. The sedimentation process plays an essential role in determining the dimensions of the settling basin in a sediment trap [1].

Sediment deposition in sediment traps is one of the most severe problems which designers and operators are often faced with. Sediment-laden flows are capable of transporting and deposit a considerable rate of sediment load in the conveyance channel, which results in a reduction of conveyance capacity of the irrigation system [2].

Therefore, measures are to be taken to exclude the sediment particles from the diverted flow into the irrigation canals. Different types of sediment extractors/extruders, such as tunnel type, vortex tubes, rectangular settling basins, are often employed for this purpose. Nowadays, the vortex settling basin has attracted considerable interest among water resources engineers. The vortex settling basin is a continuous device that applies a certain fraction of flow for flushing the sediment particles out of the diverted stream [3].

This research was significant and aimed to obtain the deposition rate in laminar flow for sediment desilting basins and non-cohesive type to be an exam in this study. A limitation of the sediment gradation to be captured >0.06cm and neglect <0.06cm and allowed to enter the irrigation system. To calculate and determine the correct formula for calculating the sediment deposition rate at the study location based on field test data and sediment transport rates in laminar flow to the sediment captured in this sediment trap.

2. BACKGROUND

The sediment dynamics of a river are sensitive to both a wide range of human activities and climate change within its drainage basin. These factors could influence sediment mobilization and transfer through action like clearing land, agricultural development, mineral extraction, urbanization, dam and reservoir construction and soil conservation and sediment control programs [4].

The velocity with which particles of specified size settle in water is a fundamental variable in physical sedimentology. The dependence of fall velocity on particle size leads to vertical size sorting when grains settle in standing water and longitudinal sorting when grains settle from a decelerating current as in deltaic environments. Sorting according to fall velocity also occurs during fluvial transport: depending on the sheer velocity of the flow, particles below some critical size travel in the suspension, whereas larger ones travel as bedload. Quantitative knowledge of how deposition velocity varies with sediment size is essential for modeling any of these or similar sorting processes and interpreting depositional environments in the rock record [5].

As a case study, this research takes an example of one weir which does not have a sediment trap. However, the policymaker will build a conventional sediment trap with a rectangular shape that requires very long settling basins. The problems that arise will be complicated to position the 150m long settling basins with their very narrow surrounding conditions. There is a connecting district road that crossing the alignment of the sediment traps settling basin in this sediment trap plan. Based on these conditions, this is part of the interest for this research to developing a model with a round and vortex desilting basin shape as an alternative to the conventional rectangular shape.

Fig.-1: Macan Weir, Located in West Java, Indonesia

Existing shapes with rectangular shape desilting basins generally suffer from two main disadvantages: (1) required of large dimension and space capered with vortex type and (2) longer settling time for sediment particles.

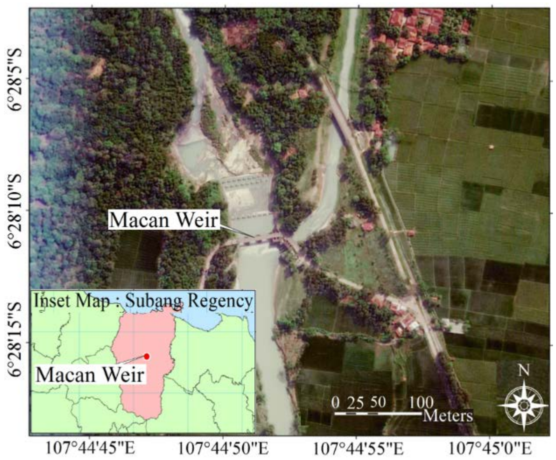

Fig.-2: Layout of Macan Weir

The existing plan for conventional construct sediment traps rectangular shape is located right side of the head structure. The flushing way out-let cross over the national bridge road. This case is an exciting point to improve the shapes of sediment traps. In this study, as a first step in determining the exact equation in sediment deposition rate, some soil investigation data have been obtained as a reference and to choose the existing and cemented sediment conditions at the bottom of the channel in the weir intake structure.

3. LITERATURE REVIEW

Sediment gravity-flow deposits are common, particularly in sandy formations, but their origin has been a matter of debate, and there is no consensus about the classification of such deposits. Sedimentation is the separation between solids and liquids from dilute slurries. This separation produces clear liquids and high concentrations of solids. The mechanism of sedimentation is described by observations in the batch settling test, where solid particles in a slurry undergo a sedimentation process in a glass cylinder [6].

Fig.-3 (a) shows a suspension in a cylinder with uniform solids concentration. Over time, the solid particles begin to settle where the rate of precipitation of the particles is assumed to be the terminal velocity at hindered-settling conditions. In Fig.-3 (b), there are several concentration zones. Region D is dominated by solid particles heavier and more rapidly settling. In zone C, there are particles of different sizes and concentrations that are not uniform [1],[7].

Area B is an area of concentration uniform and almost the same situation at first. Above area B is area A which is a clear liquid. If sedimentation is continued, the height is from each region varies, as in Fig.-3 (c) and Fig.-3 (d). Areas A and D are getting wider, proportional to the reduction in areas B and C. In the end, areas B and C will disappear, and all solids will be present in area D so that only regions A and D remain. This condition called "Critical Settling Point" is shown in Fig.-3 (e), a state where a single boundary plane is formed between clear liquid and precipitate [5],[8].

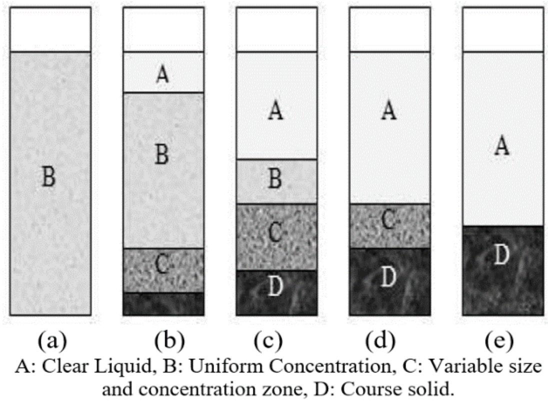

Fig.-3: Step of Sediment Deposition

The sedimentation classification is based on particle concentration and the ability of particles to interact. This classification can be divided into four types (as shown in Fig-4), namely:

a) Settling type I: discrete particle deposition, particles precipitate individually, and there is no inter-particle interaction;
b) Settling type II: deposition of flocculent particles, there is an interaction between particles so the size increases and the settling velocity;
c) Settling type III: deposition in biological sludge, where the forces between particles holding each other particles to settle;
d) Settling type IV: there is compression of the particles that have settled due to the particles' weight.

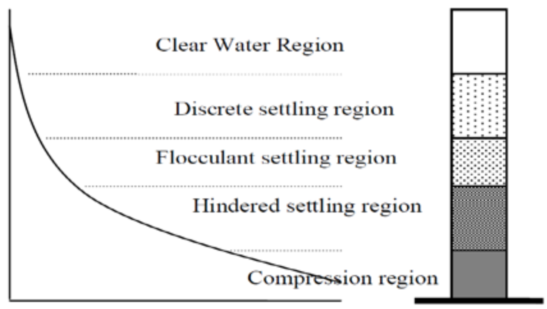

Fig.-4: Sediment Process

3.1 Continuous Process

In the initial state, the slurry concentration is uniform throughout the tube. This period is called free settling, where the solids move down only because of the force of gravity. A constant deposition is due to the concentration in the boundary layer relatively small so that the influence of the style attraction between particles, friction force, and the collision force between particles is negligible [7].

In a continuous process, there is an incoming slurry and a clear liquid that comes out simultaneously. When conditions are steady-state, the liquid level will always remain constant. The sedimentation rate is defined as the rate of reduction or decreases in the boundary area height between the slurries (deposits) and supernatant (clear liquid) at a temperature uniform to prevent a fluid shift due to convection [9].

The larger particles will drop more rapidly, causing the upward pressure of the liquid to increase, thereby decreasing the deposition decrease in larger solids. This matter makes the rate at which all the particles drop (both small and large) relative equal or constant. More and more particles settle, concentration becomes not uniform, followed by the bottom of the slurry becomes more concentrated. Concentration on the boundary increases, the particles' motion gets more complicated, and the rate at which the particles fall decreases. Condition this is called hindered settling [10].

3.2 Determining the Sedimentation Rate

In the sedimentation process, there are various ways that can be used to get the rate of settling, including:

3.2.1 The Stokes-Newton Law equation

The slow settling of small particles is resisted by the viscous drag of the laminar flow around each grain. For solitary spherical particles, it follows Stoke's law [1].

If a particle drops in the fluid because of the force of gravity, its velocity a deposition will be achieved when the number of drag force and buoyancy is proportional to the force of the gravity object [11].

On a starting particle sinking, the rate of settling at which the particles settle is expressed in equation (1):

$$V_s = \sqrt{\frac{4gD_s(\rho_s - \rho)}{3C_d\rho}} \quad (1)$$

The drag coefficient (C_d) is a function of Reynold's number. For laminar flow $R_e < 1$, C_d is determined by equation (2):

$$C_d = \frac{24}{R_e} \tag{2}$$

Reynold's number equation is presented in equation (3):

$$R_e = \frac{\rho_{D_s} V_s}{\mu} \tag{3}$$

By substituting equations (2) and (3) to equation (1), it will be obtained equation (4):

$$Vs = \frac{g D_s (\rho_s - \rho)}{18\mu} \tag{4}$$

Where Vs is the rate of settling, g is the acceleration due to gravity, and D_s is the particle's diameter, ρ_s particle density, ρ is the fluid density, μ is a liquid viscosity.

3.2.2 Fergusson-Church equation

The sedimentation process of a particle is influenced by several factors, including particle diameter, gravity, density, and viscosity [1]. Fergusson and Church formulated the sedimentation velocity equation, which is descended from Stokes Law and Laminar Drag Law. The equation for the velocity of settling is presented in equation (5):

$$V_s = \frac{S_g \ D^2}{C_1 \mu_k + \sqrt{0.75 \ C_2 \ S_g D^3}} \tag{5}$$

The definition of specific gravity S_g is presented in equation (6):

$$S_g = \frac{\rho_s}{\rho} \tag{6}$$

While the definition of kinematic viscosity presented in equation (7):

$$\mu_k = \frac{\mu}{\rho} \tag{7}$$

So that equation (5) can be reset into equation (8):

$$V_s = \frac{\rho_s \ g D^2}{C_1 \mu_k + \sqrt{0.75 \ C_2 \ \rho_s \rho g D^3}} \tag{8}$$

The parameters C_1 and C_2 take values of 18 and 0.4 for smooth spheres but somewhat higher values for natural grains, as discussed later. For particles that can be considered spherical, the values of C_1 = 18 and C_2 = 0.4. Substitute C_1 and C_2 into equation (8) so that obtained by equation (9):

$$V_s = \frac{\rho_s \ g D^2}{18 \mu + \sqrt{0.3 \ \rho_s \rho g D^3}} \tag{9}$$

Where, V_s is the rate of precipitation, g is the acceleration due to gravity, D is the particle diameter, ρ_s particle density, ρ water density, and water viscosity is μ .

3.2.3 Farag equation

Farag formulated an equation that is a refinement of the equation Stokes-Newton Law [1],[13]. The Farag equation is present in equation (10):

$$Vs = \frac{g \ dp^2 (\rho_s - \rho_f) \varepsilon_f^{\ 2}}{18 \ \mu_f b} \tag{10}$$

Where b is the constant obtained from equation (11):

$$b = 10^{1.82(1-\varepsilon_f)} \tag{11}$$

Where Vs is the velocity of precipitation, g is the acceleration due to gravity, dp is the diameter particle, ρ_s is the density of the particle, ρ_f is the liquid density, μ_f is fluid viscosity, ε_f is the fraction of volume of the fluid, and ρ_s particle density.

3.2.4 Dietrich equation

A particle released in a less dense Newtonian fluid initially will accelerate through the fluid due to its weight. Resistance to deformation of the fluid, transmitted to the particle by the surface drag on it and pressure differences across it, generates forces that act to resist the particle motion. These forces depend on the velocity and the acceleration of the particle. The grain will cease to accelerate and travel at a constant speed when the gravitational force is exactly balanced by the sum of the two resistant forces. The settling velocity V_s that arises under these conditions that we seek to predict from the fluid and particles' physical properties [12].

$$R_{eP} = \frac{\sqrt{S_g \ g} \ DD}{\mu} \tag{12}$$

$$R_f = \frac{Vs}{\sqrt{S_g} \ g \ D} \tag{13}$$

In equation (12,13), where R_{eP} explicit particle Reynolds's number, S_g specific gravity, g is gravitational acceleration, D is particles diameter and μ kinematic viscosity. R_f is dimensionless of fall velocity. Then, the Dietrich equation to calculating fall velocity V_s will be obtained as the following equation:

$$V_s = R_f \sqrt{S_g\, g\, D} \tag{14}$$

4. RESULTS AND DISCUSSIONS

Erosion and mobilization of large volumes of upland hillslope sediment are favored by the short duration, high-magnitude peak-discharge events. The sediment transport is characterized by bedload and hyper-concentrated suspended- load sediment in rapid, unconfined runoffs such as flash floods and Hortonian overland flows (Horton, 1933, 1945), and in unstable gravel-bed braided channels which wander freely over alluvial fan surfaces (Miall, 1996) [14].

Each sediment class is treated separately. Accordingly, its characteristics (the Shields number and the settling velocity) and the nominal erosion, deposition, and transport rates are computed separately for each class. Finally, the global sediment erosion, deposition, and transport rates are estimated by summing the sediment class nominal contributions. Over the model domain, the bottom-sediment mixture is defined based on the volumetric fraction of each sediment class [15].

Sediment transport involves the entrainment and movement of granular material by a shearing fluid flow. Although natural fluid flows are turbulent, experiments have shown that laminar flows can produce similar behavior in sediment transport and morpho-dynamics [16].

Factors reciprocity between the properties of water flow and sediment properties were affected by the rains cause the lifting of sediment to gravitate. Sedimentation in irrigation channels may also affect the specific energy due to irrigation canal dimensional change [17].

The first step for this study is to obtain data on the grains particles that enter the Macan river and the previously calculated sediment transport rates. The results of laboratory tests and sediment transport rates with different gradations are as follows:

Sediment Rate Macan River:			Particle Concentration Bed Load		
Sediment rate (BL)	133,042.50	ton/year	Sample-1:	0.015	gr/L
Sediment rate (SL)	146.35	ton/year	Sample-2:	0.029	gr/L
Land Erosion (LE)	55,264.30	ton/year	Sample-3:	0.017	gr/L
Annual	188,453.15	ton/year	Sample-4:	0.146	gr/L
Base Flow Macan River	8.10	M^3/S	Sample-5:	0.152	gr/L
Specific Gravity (Ms)	1.65	ton/M^3	Sample-6:	0.018	gr/L
			Average:	0.063	gr/L

Potentially Sedimentation			
Cactment Area (A)	252.00	Km^2	
Potentially Sedimentation	453.23	M^3/Year	(BL+SL+LE)/Ms / A

Capacity of Desilting Basin (Existing)			
Area	198.00	M^2	<= Wet Capacity under Spill Weir
High	1.90	M	
Capacity	376.20	M^3	

Laboratorium Test of Sediment Gradation (Approch of Dimension of Vortex):

%Sediment Composition:					
1.21	Gravel >0.06cm	5.48	M^3/Year	0.02	M^3/day
14.32	Sand 0.006-0.06cm →	64.90	M^3/Year →	0.18	M^3/day
84.47	Fine <0.006cm	382.84	M^3/Year	1.05	M^3/day

Fig.-5: Sedimentation Rate in Macan River and Sediment Composition

As shown in Fig. 5 above, that the sediment to be captured in the sediment trap that will be proposed is a non-cohesive sediment type with a grain gradation a limitation of the sediment gradation to be captured> 0.06cm and neglect diameter of <0.06cm and allowed to enter the irrigation system. The transport rate is 0.18 M^3/day.

The relationship between fall velocity Vs [dimensions L T^{-1}] and particle diameter D [L] is expected to depend on the kinematic viscosity μ [L^2T^{-1}] and density ρ_s [M L^{-3}] of the fluid, and the immersed unit weight $\gamma = (\rho_s - \rho)\, g$[M L^2 T^{-2}] of the sediment. The relation should therefore be fully describable using two non-dimensional groups [4].

The next step is to compare it visually with the plots of the previous equation for non-cohesive sediment deposition in the water at 20°C in laminar flow, as shown in Fig.-6. For diameter 0.1cm, fall velocity resulted in Stoke's Law has plotted 0.902 cm/s. Meanwhile, Fergusson-Church's Law resulted in an increase of 0.922 cm/s. The significant result of Farag's Law 1.061 cm/s. Dietrich's equation is lower than the other has plotted 0.748 cm/s.

Fergusson-Church and Farag Law, these equations are still in use because the data used in the experiment only data during free settling. In free settling, friction between particles does not affect deposition sedimentation, so the sedimentation velocity has the exact mechanism as motion free fall. Therefore, all three of these equations are still used in the experiment even though it has no variables concentration and drag coefficient (C_d).

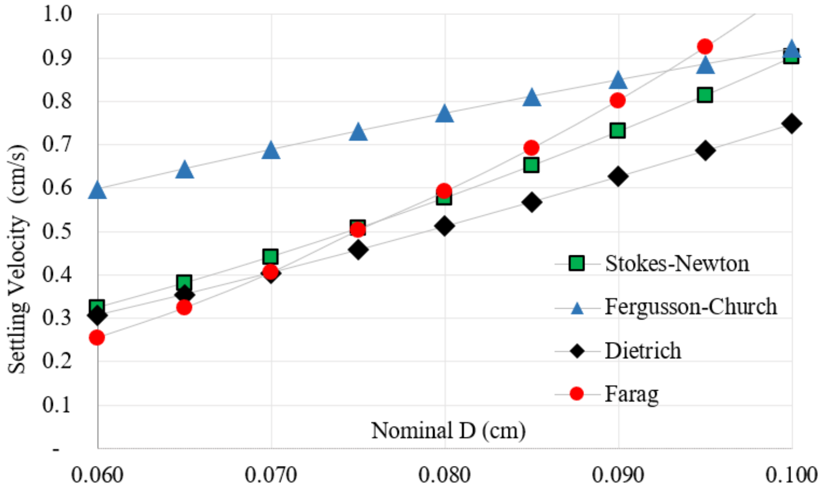

Fig.-6: Settling velocity plotted against sediment size (Calculated)

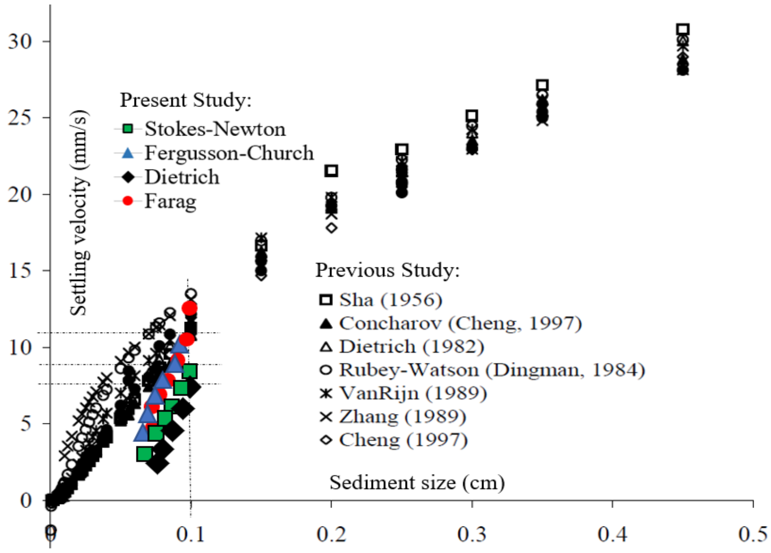

Fig.-7: Comparison plotted against the previous study B.Fentie, B.Yu, and C.W. Rose

Farag's equation, as shown in Fig-6, detailed a significant take-off curve because used variable drag coefficient (C_d). The larger the diameter of the feeding sediment particles, the smaller the drag coefficient in the fall of a sediment particle that falls on a laminar flow.

In order to compare calculations with the four equations above, it is necessary to compare with some related literature and previous studies. Some of the literature has tested the experimental sediment samples with the same gradations and diameters in the laboratory. The results of calculations with these four equations are then plotted with experimental results that have been tested by previous researchers. B.Fentie, B.Yu, and C.W. Rose (2004) was compared the formulas in sediment erosion modeling with previous researchers' datasets. Two measured datasets were used to evaluate the performance of seven formulae used to determine the settling velocity of soil particles of various sizes. The sources of these datasets are Raudkivi (1990) and VanRijn (1997). Models compared and methods of comparison, seven formulae compared in this study are (i) Sha (1956), (ii) Concharov (Cheng, 1997), (iii) Dietrich (1982), (iv) Rubey-Watson (Dingman, 1984), (v) VanRijn (1989), (vi) Zhang (1989), and (vii) Cheng (1997). The performances of these models were evaluated by visually inspecting settling velocity versus sediment size graphs from each model with measured values.

This study resulted in comparing averages from the two datasets. It appears that the formula of Cheng (1997) is the best settling velocity formula, although the other formulae are not far behind [13].

As shown in Fig-7, the comparison of calculations with four equations and datasets from previous research. From the plot results in Fig-7 above, Farag is very far from plotting the seven formulas that have been studied. Stoke and Fergusson-Church were very close to the outcome of the plot, and Dietrich pulled away to the slower deposition rate. As a result, the results given are different. For the results of reading the sedimentation graph, the errors gave initially go down with each other with increased concentration. Because it is getting bigger, the concentration of collisions that occur between particles getting bigger, while the sedimentation graph made in free settling conditions, wherein the free settling condition can be considered not there are collisions between particles, there is only friction between the walls of the solid particles with fluid that creates a drag force.

Fergusson and Church (2004) also did and tested the same thing, with datasets from previous researchers with the same experimental data and variables as this study. They assess the same utility equation in three stages.

The first is to compare it visually with the plots of some previous equations for standard conditions of quartz grains falling in water at 20°C.

We then quantify the goodness of fit of the equation and some of its predecessors to experimental data assembled by Raudkivi (1990) and Hallermeier (1981). Then, they reported new experiments on the fall velocity of natural river sands and use them for a further test of our proposed equation [13].

Predicted relation between fall velocity and diameter for quartz grains in water at 20°C according to the equation and previous authors. Straight lines in both plots show expected asymptotic trends for smooth spheres (Stokes' law with C_1=18, and constant drag coefficient C_2= 0.4).

Points labeled FIASC are experimental values from the U.S. Federal Inter-Agency Sedimentation Conference as listed in Raudkivi (1990). Upper, middle, and lower curves are for spherical, natural, and angular grains using C_1, C_2 shown in legend. Upper and middle curves are Dietrich's (1982) relation for spheres and natural grains, respectively; lower curve is Cheng's (1997) equation [5]. The results of this study plot against the research results above are shown in Fig-8 as follows:

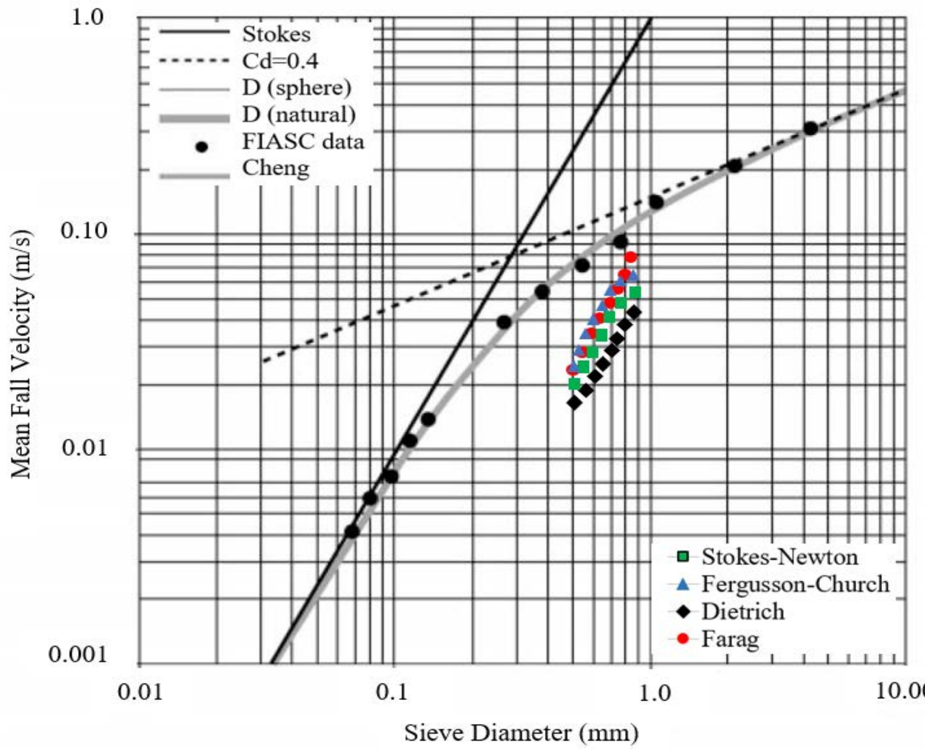

Fig.-8: Comparison plotted against the previous study Fergusson and Church

Stoke's law has several limitations:

i. It applies well only to perfect spheres (in deriving Stoke's law, the volume of spheres was used). The drag force (3π`d$\mu\omega$) is derived experimentally only for spheres. Non-spherical particles will experience a different distribution of viscous drag.
ii. It applies only to still water. Settling through turbulent waters will alter the rate at which a particle settles; upward-directed turbulence will decrease ω, whereas downward-directed turbulence will increase ω.
iii. It applies to particles 0.1 mm or finer.
iv. Coarser particles with larger settling velocities experience different forms of drag forces.

Stoke's law overestimates the settling velocity of quartz density particles larger than 0.01cm. When settling velocity is low (d<0.01cm), flow around the particle as it falls smoothly follows the form of the sphere. Drag forces F_D are only due to the viscosity of the fluid. When settling velocity is high (d>0.01cm), the flow separates from the sphere, and a wake of eddies develops in its lee. Pressure forces acting on the sphere vary. Negative pressure in the lee retards the passage of the particle, adding a new resisting force. Stoke's law neglects resistance due to pressure. Settling velocity is temperature dependant because fluid viscosity and density vary with temperature. The Fergusson-Church equation in calculating laminar in free flow is the most precise A predicted RMS Error as shown in Table-1 below:

Table-1. Root-mean-square percentage errors in predicting values of fall velocity.

Calculated Equations	Datasets Previous Authors-RMS Error
Stokes-Newton Law equation	1.06
Fergusson-Church equation	0.99
Farag equation	1.03
Dietrich	1.11

5. CONCLUSIONS

Fig-6 has shown both measured and predicted settling velocities (cm/s) as a function of sediment size. It can be seen from Fig-7 that the B.Fentie, B.Yu, and C.W. Rose (2004), with comparing seven previous authors resulted in settling velocity values for sediment 0.1cm range 9-11 mm/s. Better calculated using either the formula of Fergusson and Church (2004) close at curve plot. The settling velocity values plotted against those predicted from the seven formulae, despite some formulae being more suitable for a specific range of sediment sizes. The predictions from all seven formulae are in close agreement with the measured settling velocity values.

In Fig-7, at themselves curve, and several authors have suggested universal or multi-part relations between fall velocity V_S and particle diameter D_p that span the transitional size range in which both viscous and inertial forces are important. For quartz-density particles in the water, this range is from fine sand to granules. We have derived a simple explicit formula (equation-5) for all grain sizes, including the transitional range, from a new dimensional analysis of the problem together with the assumptions that the relation must reduce to Stokes' law for fine sediment and a constant drag coefficient for coarse sediment. The proposed equation is dimensionally correct and includes the effects of viscosity and submerged specific gravity. It contains only two coefficients, which are fewer than any previous relation, and both of them are physical parameters rather than empirical ''fudge factors'' as in most other equations. One C_1 in equation-5 is the constant in Stokes's equation for laminar settling; the other C_2 is the constant drag coefficient for particle Reynolds numbers exceeding 10^3.

Farag had developed the Stokes-Newton Law equation with takes into the variable solid concentration in the sediment, where it shows up with the variable fluid fraction in Farag's equation. However, because Farag's equation is too used for free fall objects, so for large concentrations, the Farag's equation also has a significant error. Same as the Stokes-Newton Law equation, this equation more suitable for calculating fall velocity through low concentrations. A conclusion can be drawn in this deposition rate of sediment. The Fergusson-Church equation in calculating laminar in free flow is the most precise and can be used equation tested with the sample datasets the previous authors have done.

6. ACKNOWLEDGMENTS

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