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Article

Minimum Jet Velocity for Unbounded Domain Fluidization as a New Dredging Methods

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Abstract. Unlike for the bounded domain, the minimum fluidization velocity of the unbounded fluidization domain has not been well developed. The aimed of the research is to formulate the minimum jet (holes) velocity (v_{oc}) theoretically and experimentally as the criteria for unbounded domain fluidization. Physical experiments were conducted for bounded and unbounded fluidizations of 20 cm to 45 cm thickness of sand bed. The bounded fluidization was carried out using a transparent vertical tube, whilst the unbounded fluidization was conducted on a transparent box. The fluidization discharge and pressure were measured. Empirical equations on jet holes velocity based on the experiment was developed. It was found that v_{oc} depends on the required superficial velocity at the surface of sediment deposit (v_c) and flow rate loose factor (ψ) due to unbounded domain conditions. The v_c is greater than the minimum fluidization velocity in bounded domain (v_{mf}). The conservative values of velocity conversion factor (k_s) were found to be approximately 2.0.

Keywords: Bounded domain, unbounded domain, required surface velocity, and minimum jet velocity.

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1. Introduction

In the last three decades, the study and application of fluidization technology have been developed especially in coastal and river engineering fields. Fluidization method has shown satisfactory performance and was considered worthy as an alternative method for waterway maintenance dredging. Studies and research on this method have been done using experimental, analytical and numerical models by Weisman et al. (1982, 1988, 1994) in [1], [2], & [3]; Lennon et al. (1990, 1995) in [4] & [5]; Research ranges from predicting of incipient fluidization, fluidization discharge, jet orientation, diameter and jet holes distance and formed trench dimensions. The method has also been applied by a local consulting firm to maintain channel depth in the port of Ana Maria, Florida (1986) and by the US Army Corps of Engineers for additional system of sand by passing project in Oceanside California (1991), as presented by Collins et al. (1991) and Bisher & West (1993) in [6]. Law [7] determined the pore pressure on the sediment bottom to start fluidization. Mechanism of bed fluidization using variation of velocities and frequencies of wave friction have been studied by Mehta, Williams and Feng [8]. Three dimensional numerical model conducted by Lennon and Weisman (1995) in [5] has completed the earlier study to measure the loss of the high pressure shaft by a layer of sediment. Response of fluidized sediments by a waterfall has been reviewed by Foda, DeNeale and Huang [9]. In Indonesia, research on fluidization method for channel maintenance has been done since 2000 started by Hadisantosa and Harnaeni followed by Prasojo, Sidabutar and Simanjuntak (2001). The studies included channel formation mechanism; verification jet orientation and effectiveness of the fluidization mechanism on the muddy sand. Triatmadja [10] & [11] has elaborated the sediment bed fluidization method and concluded that it was prospective as an alternative method for river mouth and waterway maintenance. Thaha et al. (2002 up to 2006) conducted a more comprehensive experimental studies among which have verified the design parameters and identified that clogging is the main problems in the operational of fluidizer system [12], comparison of required head between vertical and horizontal jet directions [13]; verification of initial pressure required for unbounded domain fluidization [14]; trench formation performance with 3D experiments [15]; The prospects of its application to Indonesian field conditions [16]; deepening the understanding of fluidization phenomena between theory and laboratory experiments [17]. Mechanisms of unbounded domain fluidization process have been observed in detailed and formulated through the development of the vortex in the sediment bed by a pressurized flows [18]. Relevant study have been undertaken by Yongxin He et al. [19]. The mechanism for the cavity evolution above the vertical jet was found that the stages were no cavity, a stable cavity, an unstable cavity propagating upward, and full fluidization. An analytical model was developed to predict the critical flow rate for full fluidization. Other study regarding an example design application of the fluidizer system at Panoang River of Bantaeng, Indonesia has been disseminated in International Conference [20].

The fluidization method is a technique in which water is injected through jet holes of buried pipes into granular medium (typically sand) causing the grains to lift up and separate. As the sediment above the pipes is fully fluidized, surface flow may remove the lifted grains downstream. Jet velocity plays an important role in determining the high pressure and discharge required to achieve fluidization conditions. The role of the jet stream, has even been developed by Ploypailin Romphophak et.al [21] to dispose of water turbidity.

Fluidization technique in the coastal engineering area is a relatively new method for navigable waterway maintenance. Since the problem of fluidization along a waterway channel is three dimensional and the fluidized area is an unbounded domain, the requirement of minimal jet velocity that is capable of creating full bed fluidization should be well understood. This paper presents the critical jet velocity as a criteria for unbounded fluidization domain.

2. Criteria for Unbounded Fluidization Domain

According to Lennon, G.P., Chang, T. and Weisman, R.N. [22] and Weisman and Lennon [1], the required minimum discharge through a jet hole to fluidize sediment bed of thickness d_b, is Q_{oc}, where Q_{oc} is a function of pressure difference between inside and outside of the fluidizer pipe and can be written as follows.

$$Q_{oc} = C_d \; A_h \sqrt{2g \frac{\Delta P_o}{\gamma}} \tag{1}$$

C_d is flow coefficient, A_h = area of jet holes, g is gravitational acceleration and γ is specific weight. Equation (1) can be solved when either Q_{oc} or ΔP_o that initiates fluidization is known. In order to determine the value of Q_{oc} or ΔP_o, the minimum velocity required for fluidization (v_c) near the sediment surface should be fulfilled. Hence, this required velocity (v_c) should be defined. The best approach to define v_c is based on v_{mf} in one dimensional fluidization as suggested by Allen [22], Snabre and Mills [23] and Goldman [24]. The minimum velocity for fluidization was developed by Richardson-Zaki (1954) in [22]; [23] & [24] as explained in the following.

The theoretical process of one dimensional fluidization (bounded domain) such presented in Fig. 1 is required to explain how to determine the v_{mf}. The flow velocity through a vertical cylinder of sand was gradually increased. The relation between the superficial velocity (v) and the pressure difference under the sand material (ΔP_o) or (Δh) showed that the increase of differential pressure (Δh) is proportional to the superficial velocity (v) until it reached a critical state of fluidization (h_e). Hence, Darcy Law is still applicable at this stage.

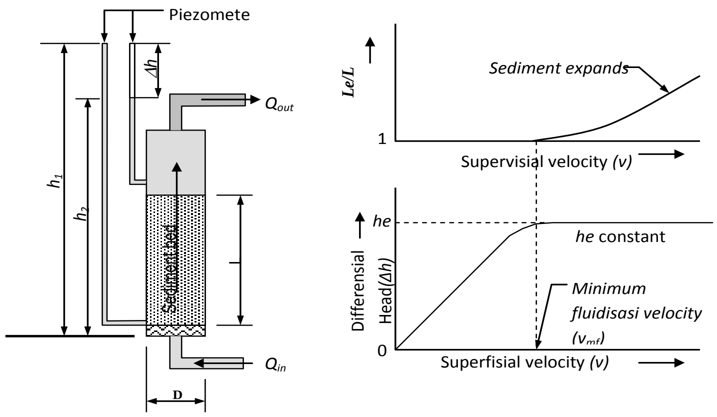

Fig. 1. Relationship between superficial velocity and pressure drop (Δh or ΔP_o).

Richardson-Zaki correlation was developed based on the relation between single sediment fall velocity and bulk sediment fall velocity as presented in Eq. 2 (Richardson, 1971 in [16]).

$$\omega = \omega_o \left(1 - C\right)^m \tag{2}$$

with ω is fall velocity for bulk sediment; ω_o is fall velocity for single particle of sediment; C is sediment concentration in normal condition. Based on the equilibrium of forces acting on the sediment in the water, the minimum fluidization velocity (v_{mf}) as the upward force to lift the bed grains should be equal to the grains fall velocity (ω). Lapidus and Elgin (1957), C.C. Harris (1959) and Anderson (1961) in [23] stated in different way that the fluidization mechanism is equal to the sedimentation mechanism in the opposite direction. At initial condition of fluidization, C is replaced by C_f and m is an empirical factor that depend on grain Reynold number. Triatmadja et al [11] further elaborated v_{mf} using sediment porosity at initial fluidization (ε_f) to replace (1 - C_f), and hence Eq. (2) can be written as Eq. (3).

$$v_{mf} = \omega_o \left(\varepsilon_f\right)^m \tag{3}$$

The $(\varepsilon_f)^m$ parameter is a factor that represents friction between particles within the flock of sediment which has to be further determined.

The next substantial discussion is how to relate the v_{mf} or v_c at the surface of sediment deposit to the jet hole velocity (v_{oc}) at the fluidizer pipe, where the v_{oc} is an important variable for Q_{oc}. There are two approaches that can be used to determine the relationship between v_{mf} or v_c to v_{oc}. First, v_{mf} may be considered as the average velocity on the cross-section of imaginary tube of fluidized sand bed. This approach requires observation of the tube diameter and the rate of the missing flow rate outside through the wall of the imaginary tube. Secondly, the correlation of the v_{mf} with a minimum jet velocity (v_{oc}) is formulated through experiment.

3. Minimum Jet Velocity & Pressure Requirement at the Hole

Based on the law of continuity, the flow across the stream tube (imaginary tube) domain can be used to formulate the relationship between the minimum superficial velocity (v_c) at the sediment surface and the minimum jet velocity (v_{oc}) at the jet holes (see Fig. 2). When v_{oc} is known, both the required pressure and flow rate at the jet holes (h_{oc} *and* Q_{oc}) can be determined.

Figure 2 presents flow through an imaginary tube from point (1) to point (2) in an unlimited domain condition. In this condition, some amount of water flow out through the imaginary tube wall (represented by arrows to the right and left). The amount of flow rate through imaginary wall can be accommodated using variable Q' and therefore the continuity equation can be expressed as Eq. (4).

$$v_1 A_1 = v_2 A_2 + Q' \tag{4}$$

where, Q' is a loss flow rate through imaginary tube wall. By using a flow rate loss factor ψ, the lost flow rate can be written as $Q' = \psi\ (v_1A_1)$. Equation (4) can then be written as Eq. (5).

$$(1-\psi)\ v_1A_1 = v_2A_2 \tag{5}$$

A_2 in the above equation is the cross sectional area at point 2 in Fig. 2. Equation (6) may be written based on Eq. (5).

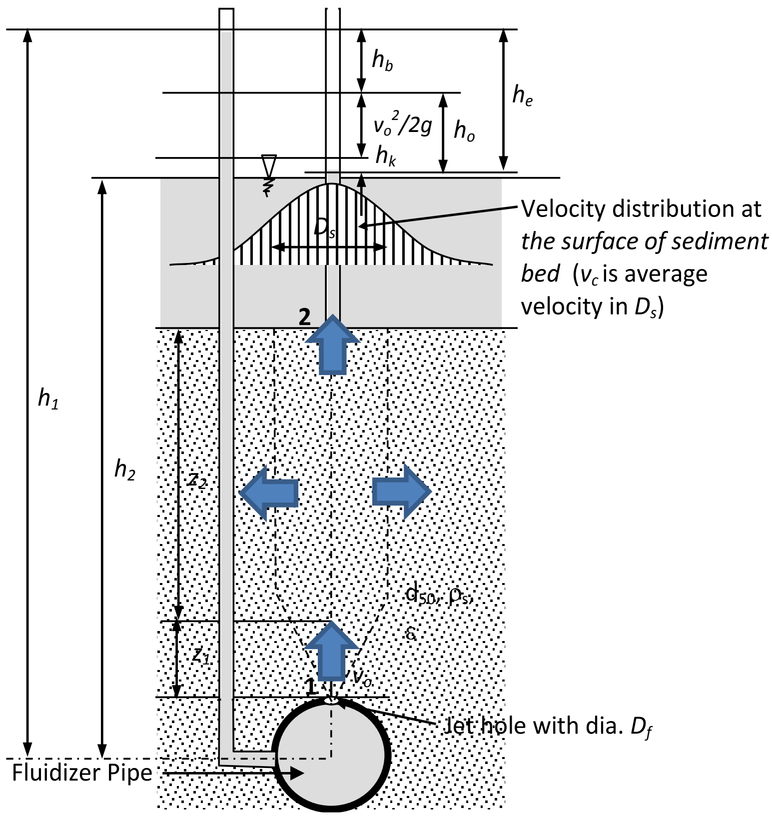

Fig. 2. Schematic of unbounded domain vertical jet fluidization [14].

$$\frac{v_1}{v_2} = \frac{1}{(1-\psi)}\frac{A_2}{A_1} = \frac{1}{(1-\psi)}\frac{D_2^{\,2}}{D_f^{\,2}} \tag{6}$$

The superficial velocity at point 2 (v_2) should be a minimum required velocity (v_c) and v_1 is a minimum required jet hole velocity or namely minimum jet velocity (v_{oc}) at point 1. The v_c may differ from v_{mf} in the bounded domain fluidization (in the real tubes where no flow rate loss), and therefore, further superficial velocity near the surface as the 2D fluidization criteria will be used v_c. D_2 is equal to the fluidized zone diameter (D_s) which is assumed to be a function of d_b (the thickness of the sediment bed) or $D_s = f\,(d_b)$. Thus Eq. (6) can be written as:

$$\frac{v_{oc}}{v_c} = \frac{1}{(1-\psi)}\left(\frac{D_s}{D_f}\right)^2 \tag{7}$$

where D_s is approximately $0.3d_b$ by Widiyanto [25], D_f is diameter of the hole. The right hand side of Eq. (7) is the flow rate lost factor through the imaginary tube wall. The relationship between v_c and v_{mf}, is assumed to be linear in which,

$$v_c = k_s\, v_{mf} \tag{8}$$

where k_s is velocity conversion factor. The v_{mf} can be rewritten from Eq. (3) such that:

$$v_{mf} = \varepsilon_f^{\ m}\left(\frac{4(\rho_s-\rho)gd}{3C_D\rho}\right)^{0,5} \tag{9}$$

where ε_f is the minimum required porosity, m is an empirical factor as a function of grain shape and Reynolds number ($Re = \omega_o d_{50}/\,\nu$).

Subtitution of Eq. (8) and Eq. (9) into the minimum required jet hole discharge for fluidization (Q_{oc}) leads to Eq. (10).

$$Q_{oc} = C_d\, A_h \frac{k_s\, v_{mf}}{(1-\psi)}\left(\frac{D_s}{D_f}\right)^2 \tag{10}$$

with C_d is discharge coefficient that was found to be 0.79 by Weisman dan Lennon [3]; A_h is the hole cross section area.

4. Experimental Procedures

One and two dimensional (1D & 2D) experiments for sand bed fluidization such as indicated in Fig. 3 and Fig. 4 have been conducted at The Hydraulic Laboratory of Gadjah Mada University, Indonesia. Three types of sand were used as the sediment bed of 1D experiments, ranging from coarse sand (d_{50} = 0.56 mm; ρ_s = 2.973 N/m^3; ε = 0.426 and ω_o = 0.052 m/s); medium sand (d_{50} = 0.28 mm; ρ_s = 2.935 N/m^3; ε = 0.426 and ω_o = 0.030 m/s) to fine sand (d_{50} = 0.17 mm; ρ_s = 3.656 N/m^3; ε = 0.432 and ω_o = 0.022 m/s). While 2D experiments were conducted using medium sand (d_{50} = 0.344; γ_d = 1.643; ε = 0.307 and ω_o = 0.0376) as the sediment bed. Vertical transparent tube of 15 cm in diameter that filled with various thickness of sand bed. Low to high flow rate of water were injected at the bottom of the vertical tube to test the fluidization. The gradient hydraulics ($\Delta h/L$) and elongation of sediment cylinder (L_e) were measured (see Fig. 3), while superficial velocity (v) was calculated based on Darcy formula.

The unbounded domain or 2D experiment were performed using a transparent box of 120 cm x 80 cm x 50 cm, equipped with a water flow circulation system (Fig. 4). Water was pump from a storage tank to a fluidizer pipe that was placed under the sediment deposit of thickness d_b. The excess water from the box overflowed throu gh a vertical pipe and return to the storage tank. In order to fluidize the sand beds, it requires a certain pressure (head) in the fluidizer pipe. By gradually increasing the flow discharges in the system, the fluidization process can be observed and recorded. The pressure in the fluidizer pipe was indicated by a manometer, while the pressure distribution within the sediment deposits were measured using pressure gauges and were directly recorded by a computer.

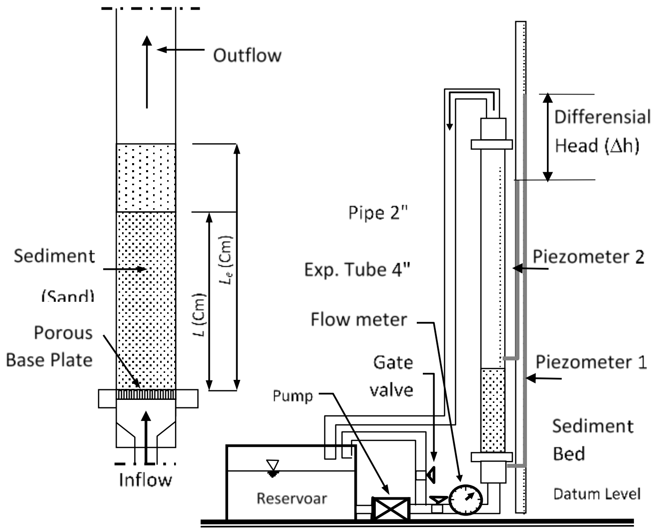

Fig. 3. Bounded domain (1D), reproduced from [17].

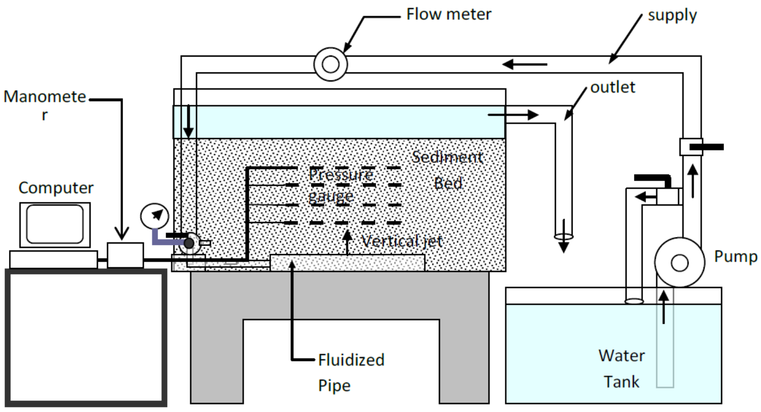

Fig. 4. Unbounded domain (2D) fluidization, reproduced from [18].

5. Results and Discussion

5.1. Minimum Fluidization Velocity (v_{mf})

A new approach to determine the minimum fluidization velocity (v_{mf}) using minimum required porosity parameter (ε_f) have been introduced in Eq. (3) and Eq. (9). Direct measurement of ε_f in the experiments is very difficult, and therefore, it was approximated based on a theoretical approach. The Carman- Kozeny equation relates hydraulic conductivity (K) to the porosity of a sediment bed as in Eq. (11).

$$K = \frac{\rho g}{5\mu} \frac{\varepsilon^3}{(1-\varepsilon)^2} \left(\frac{d}{6} \right)^2 \tag{11}$$

where μ is dynamic viscocity, ε is the porosity of grains and d is the mean diameter of sediment grain. In order to formulate ε_f, the minimum hydraulic conductivity in the initial fluidization (K_f) shall be analyzed.

The Darcy's Law is suitable for defining K_f based on the observed both the initial velocity and hydraulic gradient in the initial condition of fluidization since at tha coditions the flow is still laminar and hence:

$$v_{mf} = K_f \frac{dh}{L} \tag{12}$$

In which, dh/L is to be observed at initial fluidization and v_{mf} is calculated. Bear (1972) stated that dh/L is approximately equal to 1 in [22]. Wen and Yu (1966) in [22] suggested that the value of v_{mf} is approximately 1/10 times of ω_o for large size of particles and 1/100 times of ω_o for small size of particles. With these in mind and by using Eq. (11) and Eq. (12), it is possible to write Eq. (13).

$$\frac{K_f}{K} = \eta \frac{C}{R_e} \text{ With } R_e = \frac{vd}{\nu} \tag{13}$$

where, η is v_{mf}/ω_o ranging from 0.01 to 0.1 for fine to coarse sediment respectively, while C is a coefficient that follows Eq. (14).

$$C = \left[\frac{240}{dh/dL} \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\rho_r}{C_D} \right] \tag{14}$$

Figure 5 shows the experimental results using medium sand (between fine and coarse sand) compared with Eq. (13).

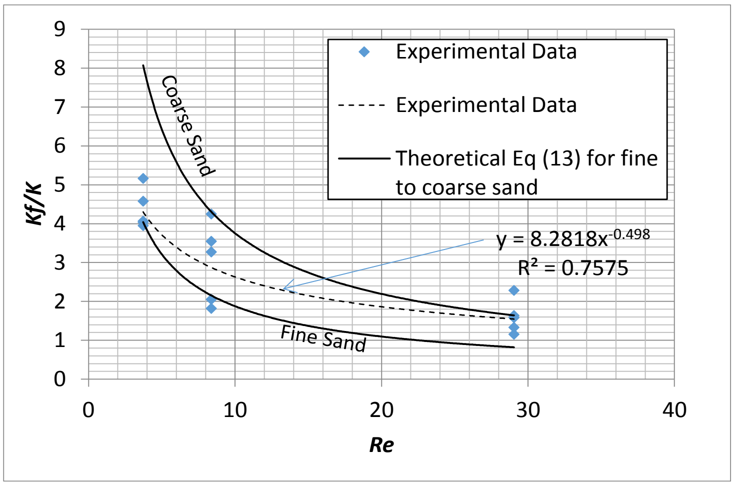

Fig. 5. K_f/K as a function of Re between theoretical approach and experimental data.

Figure 5 indicates that the theoretical approach was within the range of the experimental data. The empirical equation can be simplified and written as Eq. (15).

$$\frac{K_f}{K} = \frac{8.28}{\sqrt{Re}} \tag{15}$$

From Fig. 5, both Eq. (13) and Eq. (15) shows that R_e has a strong influence on K_f/K. The curve indicates that the smaller is R_e the greater is K_f/K. Critical porosity (ε_f) may be further defined in term of K_f/K from the experimental data in Fig. 6 and Eq. (16).

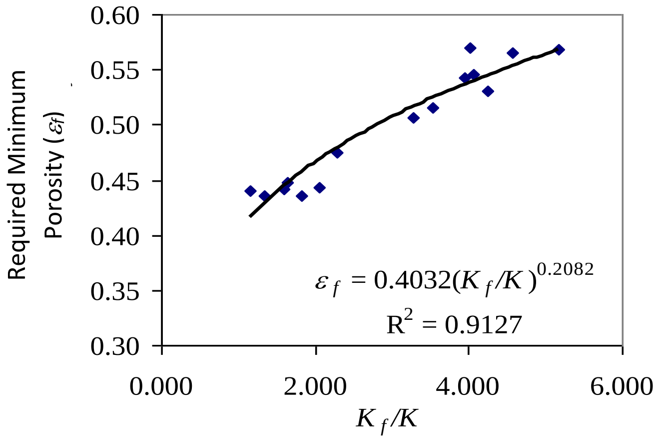

Fig. 6. The relationship K_f/K with ε_f .

$$\varepsilon_f = 0.40\left(\frac{K_f}{K}\right)^{0.21} \tag{16}$$

Figure 6 shows a strong relationship between K_f/K with ε_f, where ε_f increases with the increasing K_f/K or finer sediment grain size. This result is in agreement with the relationship K–ε according to Carman-Kozeny. Based on the experiment, the value of m is calculated and illustrated as a function of R_e in Eq. (17) and is compared to the value of m of the Richardson-Zaki correlation in Fig. 7.

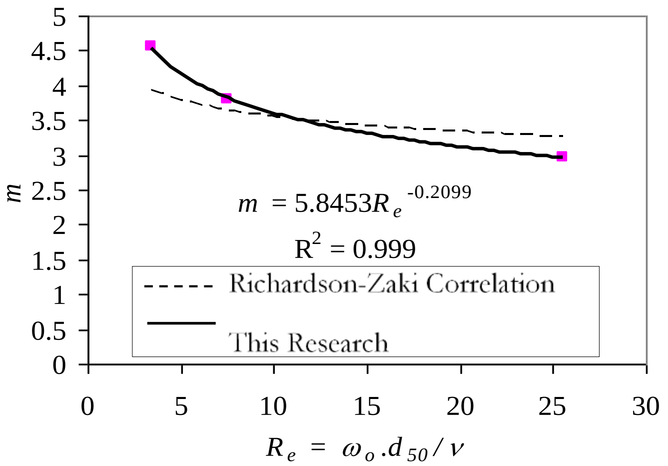

Fig. 7. Relationship of Re with m.

$$m = 5.85R_e^{-0.21} \tag{17}$$

Figure 7 shows that m reduces as R_e increases. This means that finer grain size produces higher m. The empirical relationship of m and R_e can be written as in Eq. (17), with $R_e = \omega_o.d_{50}/\nu$ in the range of 1 to 30. Based on Fig. 7, the relation of R_e to v_{mf} was generally closed to the Richardson-Zaki curve. Furthermore, the v_{mf} can be computed using Eq. (9). The required variables are defined using Eq. (15), Eq. (16) and Eq. (17). The results are compared with the previous studies in Fig. 8.

Figure 8 indicates that the value of the present v_{mf} is similar to previous researches by Richardson-Zaki, Davidson-Harrison and Yu Wen.

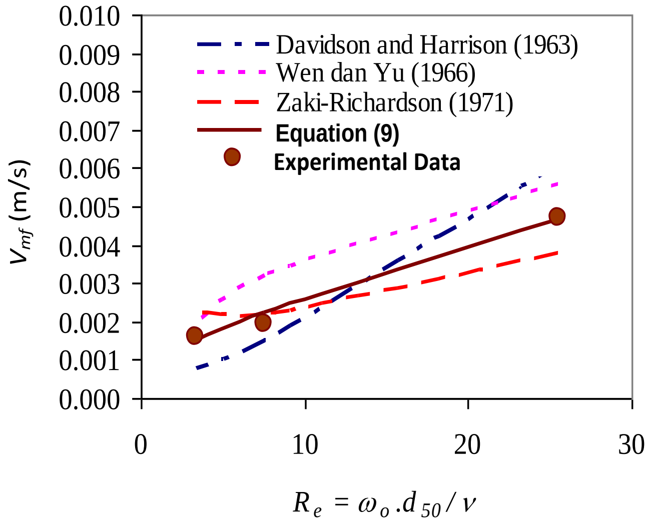

Fig. 8. The comparison of the v_{mf} value of previous results.

5.2. Formulation of the Minimum Required Jet Velocity (v_{oc})

Minimum jet velocity (v_{oc}) and holes discharge (Q_{oc}) can be calculated based on Eq. (7) and Eq. (10). Both equations require variable k_s which has not been known theoretically. Hence k_s was defined based on experimental data using Eq. (10). In this case, ψ was equal to 0.4 [2] and D_s was taken as $0.3d_b$ (Widiyanto, [25]) whilst v_{mf} was calculated based on Eq. (9). By varying k_s, the value of v_{oc} or Q_{oc} can be found. The results of the simulated value of v_{oc} or Q_{oc} are given in Fig. 9 for k_s equal to 1.0, 2.0 and 2.4 together with the measured data.

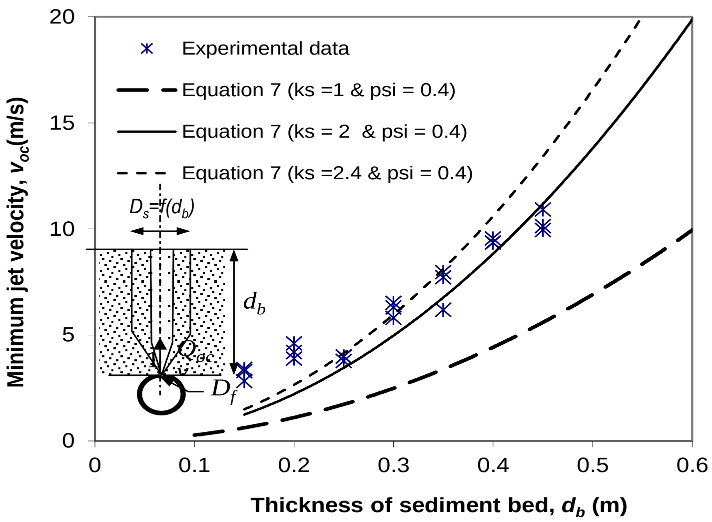

Fig. 9. Relationship d_b-v_{oc} in experimental and theoretical for k_s = 1; k_s = 2 & k_s = 2.4 in ψ = 0.4.

Figure 9 suggests that a value of k_s equal to 1 produces v_{oc} that is much lower than the experimental results, while k_s equal to 2.4 produces v_{oc} higher than the experimental results. The best fit is achieved when k_s equals 2.0. The finding k_s gives an understanding that the achievement of fluidized conditions in unbounded domain is require 2 times of minimum superficial velocity (v_c) compared to the velocity requirement for bounded domain or cylindrical tube fluidization (v_{mf}). This is because about 40% of the flow rate is lost in the horizontal direction of the media. The implication is that it requires greater discharge and pressure (head) than in cylindrical tube fluidization.

Based on the finding value of k_s as described above, the jet velocity (v_{oc}) can be formulated as in Eq. (18).

$$\frac{v_{oc}}{v_{mf}} = 0.34\left(\frac{d_b}{D_f}\right)^2 \tag{18}$$

with v_{oc} is the minimum single jet velocity; v_{mf} is the minimum fluidization velocity of Eq. (3); d_b is the thickness of sediment; D_f is the diameter of jet hole.

6. Conclusions

Equation of the jet hole critical velocity (v_{oc}) has been established. The v_{oc} depends on the required surface critical velocity (v_c) and flow rate loose factor (ψ) due to unbounded domain conditions. As expected, the critical velocity for unlimited domains (v_c) is greater than the minimum fludization velocity for limited fluidization domains (v_{mf}). The conservative values of k_s were found to be approximately 2.0. These findings can be used to facilitate fluidizer system design as an alternative dredging method for the purpose of maintaining the river channel, river mouth and other waterways in coastal environment.

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