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ABSTRACT

Although many papers have reported suction influence on sediment transport, only few of them considered effects of suction zone length on sediment transport rate. In this study, experiments were conducted to investigate suction effects on sediment transport rate in a horizontal conduit with a suction zone with variable lengths. The results show that at the same suction intensity in the form of suction velocity ratio, the sediment transport rate increases with suction zone length, while all the data collapse if suction intensity in the form of suction rate ratio is used. Moreover, velocities measured using Particle Image Velocimetry are used to explain the effect of suction zone length on the transport rate. Finally, a modified densimetric Froude number involving the effect of suction rate in terms of changes to the near-bed streamwise velocity is developed on the basis of this finding.

Keywords: Closed-conduit flow; particle image velocimetry; sediment transport; suction rate; suction zone length

1 Introduction

Suction is a type of seepage flow across a permeable boundary in the downward direction, a phenomenon that is common in nature and engineering practice. Its effect on the flow field and sediment transport rate has been reported by many researchers. A careful search of the literature reveals that two opposing conclusions can be found on suction effects on sediment transport. The first group of researchers (e.g., Oldenzien and Brink 1974, Francalanci *et al.* 2008) concludes that suction reduces the sediment transport rate, while Willetts and Drossos (1975), Lu and Chiew (2007), Liu and Chiew (2012) and Cao and Chiew (2014), amongst others, arrive at an opposite conclusion. Table 1 shows the experimental conditions and the inferences made by these researchers. First, the table clearly reveals that different results have been obtained by these researchers. Second, it also shows that some of these researchers utilized suction velocity V_s , while others used suction rate Q_s as the variable in analyzing suction effects on sediment transport rate. It may be inferred from this observation that conflicts still exist on whether V_s or Q_s is a more appropriate variable to account for sediment transport rate. Finally, as suction zone length is fixed in most of these studies, its effect has rarely, if ever, been reported. In her doctoral study, Liu (2010) did change the suction zone length and studied its effect on sediment transport rate. However, she used V_s as the variable in her analysis, which is different from the approach in this study.

Contrary to all the studies listed in Table 1 (except for Cao and Chiew 2014), only the present study is carried out in a closed conduit instead of an open-channel flow. This is because in open-channel flow that is subjected to suction, the abstraction of water causes both

the flow rate and water depth to reduce, leading to an undefined change in the local flow velocity. This is because whether the velocity increases or decreases is related to the relative reduction of the flow rate and flow depth when suction is applied. In other words, if the rate of reduction of flow depth is more than that of the flow rate, the resulting velocity evidently will increase. This uncertainty could be an important factor in contributing to the disagreement amongst the results found in published literature. Many researchers (Maclean 1991, Chen and Chiew 2004, Lu *et al.* 2008, Dey and Nath 2010, Dey *et al.* 2010, Dey *et al.* 2011) have conducted experiments to investigate seepage effects on flow characteristics in open channel flow. Amongst them, Dey and Nath (2010) experimentally measured the velocity and turbulence in open channel flow with seepage. In their experiments, they observed the water depth changes when injection is introduced. They further commented that it was extremely difficult to experimentally adjust the water depth in the presence of seepage or suction to be the same as that without. In order to eliminate the effect of flow depth, the present study is conducted in a closed conduit in which the flow depth, or more appropriately, the flow cross-sectional area remains constant regardless of the amount of flow abstraction caused by suction. With this approach, one can better examine suction effects on sediment transport rate and further attempt to clarify the discrepancy highlighted above. From another perspective, a higher pressure will act on the boundaries of a closed conduit than that of an open-channel flow, possibly resulting in changes to the sediment transport rate. Although some previous researchers, e.g., Bagnold (1966) had surmised that pressure may influence bedload transport, its explicit impact on bed sediment mobility is still not very well-established as few detailed studies on this topic can be found in the literature. In this study, no attempt is explicitly made to compare the sediment transport rate subjected to the same amount of suction in open-channel and closed-conduit flows as suction effects on sediment transport in closed-conduit flow has rarely been reported. Previous researchers (e.g., Elena *et al.* 1977, Schildknecht *et al.* 1979, So and Yoo 1987) have studied suction effects on the flow behavior in a closed conduit experimentally and numerically, but they did not consider its influence on sediment transport rate. Although Cao and Chiew (2014) investigated suction effects on sediment transport rate in closed-conduit flow, they did not vary the suction zone length.

Consequently, the present experiments were carried out to investigate suction effects on sediment transport in a closed conduit with three different suction zone lengths. The results were compared with Liu's (2010) data obtained from tests conducted in open channel flow. Moreover, velocity measurements were conducted using Particle Image Velocimetry and the data are used to explain the effect of suction zone length. Finally, with the present data and those from Liu (2010), a modified dimensionless Froude number is developed.

2 Experimental setup and procedures

2.1 Experimental setup

The experiments were conducted in the same closed conduit as that used in Cao and Chiew (2014). The details of the experimental setup can be found in that paper and will not be repeated here although the schematic drawing of the conduit is reproduced in Fig. 1 for clarity. The suction zone length, L is varied ($L = 0.1, 0.2$ and 0.5 m) in the same way as that used in Liu (2010) so that meaningful comparison with her data may be conducted, i.e., by placing a plastic plate on the bottom of the suction zone as illustrated in Fig. 2 ($L = 0.2$ m). Uniformly distributed sediment with median grain size, $d_{50} = 0.84$ mm, geometric standard deviation = 1.17 and specific gravity $S_s = 2.66$ is used in the experiments.

The streamwise velocity profiles in the near-bed region were measured by using a high speed camera combined with the Particle Image Velocimetry (PIV) technique. The PIV measuring system consisted of a 4W air-cooling laser with wave length of 532 nm as the light source and a high speed camera. The laser beam emitted from the laser source, which was 1 mm thick, was cast downward into the water through the Perspex top of the flume. Aluminum particles having diameter of 10 μm with specific density of 2.7 were used as the seeding particles in the study. Using Stoke's law, the fall velocity of the aluminum particles is computed to be less than 10 $\mu\text{m/s}$, which is much smaller than the flow velocity of interest in this study. The high speed camera (Olympus, i-speed 3), which has 2-gigabyte memory storage and 1280 $\times$ 1024 pixel resolution was used to capture images of the particle laden flow. A 105-mm focal lens was mounted with the high speed camera operated at 300 frames per second in the experiments. Velocity fields were determined by cross-correlation analyses. Here, a multi-grid processing technique proposed by Hsieh (2008) is adopted to enhance the accuracy of velocity calculation. This multi-grid process, which starts and ends with 32 $\times$ 32 and 8 $\times$ 8 pixels, respectively, uses interrogation windows with 50% overlap in the cross-correlation analysis.

In this study, the laser light source, which was mounted on top of the test section, could be controlled with an accuracy of 0.1 mm along the side wall of the flume. The camera captured the flow field via a glass sidewall. For the measurements of the axial (u) and vertical (v) velocities, the laser light sheet was cast vertically downward from the Perspex top through the center-line of the conduit, as shown in Fig. 3. Both the light source and camera could be moved along and parallel to the sidewall of the conduit so that velocity measurements were conducted for a suction zone with length of 50 cm, from $x = -1$ cm to 25 cm (x denotes the horizontal distance from the leading edge of the suction zone). The origin ($y = 0$) of the vertical coordinate is defined as the plain where the horizontal laser beam just passes the bed

surface.

2.2 Experimental procedure

To investigate suction effects on the sediment transport rate, a total of three series of tests, each with a different suction zone length, were conducted in the study. In the first series of tests or Series A, the suction zone length is 0.5 m. In the second and third series of experiments or Series B and C, the suction zone length is 0.2 and 0.1 m, respectively. The detailed procedures for the measurement of sediment transport rate in all the three series can be found in Cao and Chiew (2014). Briefly, several minutes after the commencement of each test, the sand particles transported from upstream are collected in the sand trap for duration of 15 minutes. At the end of each test, the collected sand was dried in an oven and the mass weighed. With the known mass, sediment density and collection time, the volumetric bedload transport rate, q_b can be calculated.

Second, two additional series of tests were conducted in the conduit with suction zone length of 0.5 m to measure the near-bed flow field. The undisturbed approach flow rate, Q_0 was kept as 7 L/s in both series of tests.

The first series of tests or Series I aim to study the effect of different suction rate Q_s on the near-bed flow field in closed-conduit flow. The procedure of Series I is as follows:

- (i) Open the roof of the flume and level the sand surface to the adjacent bed (false floor). Then close the flume top and tighten the screws.
- (ii) Place the laser on the top of the flume and fix the PIV as mentioned previously.
- (iii) Turn on the pump slowly at a low flow rate and allow the water to fill the flume.
- (iv) Adjust the pump to $Q_0 = 7$ L/s. Note that in the entire experimental process, the reading of the main flow meter is kept as a constant. Although a slight increase in the main flow rate is detected as soon as the suction valve is open or adjusted, the main flow valve was adjusted correspondingly to ensure that $Q_0 = 7$ L/s.
- (v) After about two minutes when the flow has stabilized, measure the near-bed flow field at $x = 25$ cm (x denotes the horizontal distance from the leading edge of the suction zone) using the high-speed camera. After that, turn off the main pump and the suction valve.
- (vi) Repeat the above steps and adjust Q_s to vary from 0 to 2.1 L/s.

The objective of Series II is to measure the streamwise velocity flow profiles at different locations along the suction zone. The procedures in this series of test are the same as in Series I except that Q_s was kept constant at 0.9 L/s while measurements were conducted at 4 locations, namely, $x = -1$ cm, 2 cm, 10cm, and 25 cm.

After obtaining the flow field data, a continuity check was performed following the method proposed by Chang *et al.* (2001) and used in Lin *et al.* (2004) to calculate the flux at each grid element $q = \left| \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right| dA$ (in which u and v are time-averaged velocities in the axial and vertical directions, respectively; dA is the area of the grid in a vector field; and $dA = \Delta x \times \Delta y$; $\Delta x = 0.9$ mm, $\Delta y = 0.45$ mm for each grid) in the mean velocity field. Assuming the flow to be two-dimensional, the possible error, ε may be estimated by using the concept of continuity as $\varepsilon = \left| \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right|$. Additionally, by assuming that ε could be equally split into the u and v components, the error in each velocity component may be calculated as $u_{\text{error}} = (\varepsilon / 2) \Delta x$ and $v_{\text{error}} = (\varepsilon / 2) \Delta y$. Accordingly, the error of the velocity vectors is found to be less than 0.7 cm/s. Similarly, by substituting u_{error} and v_{error} into $q = \left| \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right| dA$ for flux error analysis, the flux error is found to be larger and more sensitive than the velocity error. The error in the flux of the velocity field is defined as q/q_0 where $q_0 = U_0 \cdot \Delta y$, U_0 is mean velocity of the approach flow. The maximum error in the flux of the velocity field is about 5.8%, which may be considered to be small, indicating that the PIV measurement in the study is reliable.

3 Results and discussions

Tables 2 shows the test conditions and measured sediment transport rates for Test Series A ($L = 0.5$ m and $L/h = 5.40$, h = water depth), B ($L = 0.2$ m and $L/h = 2.16$) and C ($L = 0.1$ m and $L/h = 1.08$). It must be noted at the outset that Q_0 used in all the tests is 7 L/s, which corresponds to a computed approach shear velocity ratio, $u_{*0} / u_{*0c} = 0.997$ (without suction), in which u_{*0} = undisturbed approach shear velocity and u_{*0c} = critical shear velocity for bed sediment entrainment. The former is computed by using the mean velocity computed from Q_0 and the friction factor estimated using the revised Nikuradse friction factor diagram after Brownlie (1981) (Garcia 2008). By adopting the side-wall correction method described in Chiew and Parker (1994), the different roughness on the sides, bottom and top of the conduit can be accounted for. The latter (u_{*0c}) is calculated using the Shields function in van Rijn (1984). With the shear velocity ratio being smaller than unity, the bed sediment particles in the conduit are expected to move very slowly (Buffington 1999) and experimental observations validated this condition. Test B-1 corresponds to such a condition (with suction zone length = 0.2 m) and the sediment transport rate q_b is measured to be 0.3×10^{-9} m²/s. In the other extreme, Test A-9 shows the largest measured volumetric bedload transport rate per

unit width, $q_b = 0.2012 \times 10^{-6} \text{ m}^2/\text{s}$. Thus the maximum average scouring depth over the suction zone with length = 0.5 m, $d_s = q_b \times t/L = 0.2012 \times 10^{-6} \times 15 \times 60 / 0.5 \approx 0.36 \text{ mm}$ for the test duration = 15 minutes. As $d_{50} = 0.84 \text{ mm}$, less than one layer of sand is entrained by the flow and scouring is negligible. Moreover, neither ripples nor dunes were observed during the experiments. Therefore, the sediment bed remains essentially planar for the given sediment transport rates within the entire 15-minute test duration for all the tests. In the experiments, the undisturbed approach flow rate, $Q_0 = 7 \text{ L/s}$ is chosen to be the baseline condition and all tests were conducted with this approach flow rate.

Figures 4a and 4b show the dimensionless volumetric sediment transport rate,

$$\Phi = \frac{q_b}{\sqrt{d_{50}^3 g (S_s - 1)}} \text{ plotted against the normalizing parameters } V_s/U_0 \text{ and } Q_s/Q_0,$$

respectively. Although Φ increases with both V_s/U_0 and Q_s/Q_0 , the increasing trends for different suction zone lengths show variations as illustrated in the figure. Figure 4a reveals that at the same V_s/U_0 , Φ differs significantly for different suction zone lengths. Generally, Φ increases with increasing suction zone length for the same V_s/U_0 . For instance, Fig. 4a shows that at $V_s/U_0 = 3.2\%$, $\Phi \approx 9 \times 10^{-6}$, 2.5×10^{-5} and 2×10^{-3} for the case with $L/h = 1.08$, 2.16 and 5.40 respectively. The volumetric sediment transport rate associated with $L/h = 5.40$ is found to be more than 220 times that associated with $L/h = 1.08$. In other words, a five-fold increase in suction zone length has led to more than 220-fold increase in sediment transport rate! On the other hand, Fig. 4b shows that the data collapse into one unique curve for different suction zone lengths. Note that the only difference between Figs. 4a and 4b is that the former utilizes V_s/U_0 and the suction zone length as two independent variables, while the latter incorporates both the effects of V_s/U_0 and suction zone length into a new parameter Q_s/Q_0 . Therefore, it may be inferred from the data that the latter figure is superior in that the sediment transport rate is correlated to just one singular parameter, which is able to incorporate both the length of suction zone as well as V_s/U_0 effects. Another inference one may deduce from the data in the figure is that the effect of either Q_s/Q_0 or V_s/U_0 on Φ is negligible for small values of these parameters until a critical value is reached. Beyond this threshold, the sediment transport rate increases abruptly.

A cursory examination reveals that $Q_s/Q_0 = V_s/U_0 \times L/h$, which means that Q_s/Q_0 includes both the effects of the suction velocity ratio, V_s/U_0 and mass rate transferred across the permeable bed due to suction (mass rate = $\rho V_s b L = \rho Q_s$) on sediment transport rate. Figure 4 shows that increasing L when keeping V_s as a constant has the same effect as increasing V_s when keeping L as a constant. In both instances, the sediment transport rate is increased because of the increase in either the mass or velocity. In order to confirm this behavior, a comparison is conducted with the data in Liu (2010) conducted in open channel flow. In

order to carry out a logical comparison, dimensionless numbers are determined through the conduct of a dimensional analysis to account for all the possible factors that may influence sediment transport rate. It is assumed that the volumetric sediment transport rate per unit width, q_b is a function of the following independent variables, including d_{50} ; sediment density, ρ_s ; water density, ρ ; gravitational acceleration, g ; sediment porosity, n ; hydraulic conductivity, K ; V_s , U_0 , shear velocity without suction, u_{*0} ; L and h . Hence, the general function of q_b may be expressed as follows:

$$q_b = f(d_{50}, \rho_s, \rho, g, n, K, U_0, V_s, u_{*0}, L, h) \quad (1)$$

The variables d_{50} , ρ and g were chosen as repeating variables for the dimensional analysis,

resulting in the following nine pi terms: $\frac{q_b}{\sqrt{d_{50}^3 g}}$, $\frac{\rho_s}{\rho} = S_s$, n , $\frac{K}{\sqrt{d_{50} g}}$, $\frac{U_0}{\sqrt{d_{50} g}}$, $\frac{V_s}{\sqrt{d_{50} g}}$,

$\frac{u_{*0}}{\sqrt{d_{50} g}}$, $\frac{L}{d_{50}}$ and $\frac{h}{d_{50}}$, which are reduced to the following three dimensionless groups:

$$\Phi = \frac{q_b}{\sqrt{d_{50}^3 g} (S_s - 1)} = f \left\{ \frac{u_{*0}^2}{(S_s - 1) d_{50} g}, \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{V_s}{K} \cdot \frac{L}{h} \right] d_{50} g} \right\} \quad (2)$$

where Shields' parameter, which describes the initial condition of sediment bed before

seepage is introduced, $\tau_{*0} = \frac{u_{*0}^2}{(S_s - 1) d_{50} g}$ and $\Omega_{Q_s} = \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{V_s}{K} \cdot \frac{L}{h} \right] d_{50} g}$,

which is a new modified Froude number that includes the effect of L and h , based on

$$\Omega_{V_s} = \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{V_s}{K} \right] d_{50} g} \quad \text{that was developed earlier by Liu (2010).}$$

Because $Q_s/Q_0 = V_s/U_0 \times L/h$, Ω_{Q_s} may be re-written as,

$$\Omega_{Q_s} = \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{Q_s}{Q_0} \cdot \frac{U_0}{K} \right] d_{50} g}, \quad \text{which contains the ratio of the suction rate and}$$

undisturbed flow rate, Q_s/Q_0 .

The new dimensionless parameter Ω_{Q_s} contains Q_s/Q_0 , which is the product of V_s/U_0 and L/h . The former accounts for the suction velocity effect, which is implied in the original Ω_{V_s} , while the latter accounts for the mass effect. The product of the suction velocity and mass rate across the sediment bed is equivalent to the momentum transfers across the

sediment bed, which is related to the combined effect of V_s/U_0 and L/h on sediment transport. When there is no suction, the undisturbed approach flow momentum, $M_0 (= \rho \times Q_0 \times U_0 = \rho \times U_0^2 \times bh)$ will affect the sediment transport rate, q_{b0} . When suction is present, V_s and L will reduce the effective approach flow rate, Q_0' as $Q_0' = Q_0 - V_s \cdot L \cdot b$ (b is width of the conduit), causing the approach momentum, $M' [= \rho \times Q_0' \times U_0' = \rho \times (U_0 - V_s \cdot L/h)^2 \times bh]$ to be smaller. With the momentum transfer across the sand bed $M_t (= \rho \times V_s^2 \times bL)$, they will influence the sediment transport rate, q_b . Hence, the ratio of q_b/q_{b0} should be a function of $(V_s/U_0 \times L/h)$ or Q_s/Q_0 rather than V_s/U_0 per se.

The hypothesis that Ω_{Q_s} is a better parameter than Ω_{V_s} for use to correlate suction with sediment transport rate may be validated by using the experimental results of Liu (2010). In her doctoral study, Liu (2010) conducted the experiments in an open channel flume that is 30 m long, 0.7 m wide and 0.6 m deep, with a suction zone = 0.4 m depth located in the middle of the flume. The flume and suction zone is filled with uniform sand with $d_{50} = 0.48$ mm and three different zone lengths = 0.5, 1 and 2 m. The way the suction zone length was varied is the same as that in the present study, i.e., by inserting an impervious plastic plate with the specific length below the sand (see Fig. 2). In total, four sets of experiments with four different values of $u_{*0}/u_{*0c} = 0.98, 1.05, 1.08$ and 1.16 , were conducted. Figs. 5a and 5b plots all the data of the present study in closed-conduit flow ($u_{*0}/u_{*0c} = 0.997$) and that from Liu (2010). It should be noted that Figs. 5a and 5b are plotted with Φ as a function of Ω_{V_s} and Ω_{Q_s} , respectively on a log-log scale in order to provide a better display of all the data.

Figure 5 clearly shows that Φ is empirically better correlated to Ω_{Q_s} than Ω_{V_s} . Since sediment transport rate is closely related to the flow field, the results in Figs. 5a and 5b may be explained by examining the flow behavior. Consideration of the data in Fig. 5a reveals that on the one hand, decreasing Ω_{V_s} leads to an increase in Φ , indicating that larger V_s/U_0 will result in larger q_b when the suction zone length is fixed. This probably is because the horizontal approach velocity at the particle level, u_b increases with larger V_s/U_0 , leading to a larger driving force that increases sediment transport rate. Chen and Chiew (2004) had earlier used Laser Doppler Anemometry to measure the flow characteristics in a 32 m long open channel with a 2-m length suction zone. They found that the slip velocity (streamwise velocity at the interface between fluid and particle) increases when a larger V_s/U_0 is present. Similar results also can be found in Maclean (1991). To verify if the same result also applies in a closed conduit, streamwise velocity profiles at a fixed horizontal location $x = 25\text{cm}$ (x denotes the horizontal distance from the leading edge of the suction zone) in the near-bed region subjected to six different V_s/U_0 were measured using the PIV in the present study and the result is shown in Fig. 6. The figure, which shows the near-bed streamwise velocity

profile at the same distance from the leading edge of the suction zone, reveals that the streamwise velocity in the near-bed region (below the dashed line in Fig. 6; $y < 0.2\text{cm}$), u_b generally increases with increasing V_s/U_0 . Consequently, one may surmise that a larger driving force is present to entrain the sediment particles at a high rate, resulting in a larger q_b . On the other hand, Fig. 5a also shows that with the same V_s/U_0 , a larger L/h leads to a larger q_b , a phenomenon that is also related to the flow field. Chen and Chiew (2004) found that the streamwise velocity profile becomes more uniform as the flow moves into the suction zone. To examine if the same behavior is present in closed-conduit flow, streamwise velocity profiles in the near-bed region at four horizontal locations, i.e. $x = -1, 2, 10$ and 25 cm were measured and the results shown in Fig. 7. The measured data show that the near-bed velocity increases significantly (below the dashed line in Fig. 7; $y < 0.2$ cm) and the velocity in the upper region does not change as significantly as that in the lower region, which means that the velocity profile has become more uniform as x increases, a behavior that is consistent with the data of Chen and Chiew (2004). It can thus be inferred that the approach velocity at the near-bed particle level, u_b increases as L becomes larger.

Based on these comparisons, one may deduce that the effect of suction by varying the suction intensity (V_s/U_0) is the same as that by varying the suction zone length, e.g., both of which causes the streamwise velocity profile in the near-bed region to become more uniform and the horizontal velocity, u_b at the particle level to increase. Since increasing u_b will lead to a larger driving force, the sediment transport rate will correspondingly increase. Examination of the data in Fig. 5b reveals that decreasing Ω_{Q_s} also leads to an increase in Φ , showing that increasing Q_s/Q_0 leads to a larger q_b . This trend supports the hypothesis outlined above. However, a major difference between Figs. 5a and b is that all the data with the same u_{*0}/u_{*0c} and different L/h collapse when Φ is plotted against Ω_{Q_s} . This confirms that increasing V_s/U_0 (velocity effect) and increasing L/h (mass effect) has the same effect, i.e., both can increase the sediment transport, and their combined effects may be incorporated into a single parameter, namely Ω_{Q_s} .

At this juncture, one may ask the question: When V_s/U_0 and h remain constant, will q_b increase indefinitely with L ? One may conduct a thought experiment and the result is illustrated in Fig. 8, which shows that q_b will first increase with increasing L until a critical value, beyond which q_b will decrease and gradually approaches zero when L becomes very large. The reason for the reduced sediment transport rate is because in the presence of suction, water is continuously abstracted from the suction zone. Although the velocity effect dominates initially, causing q_b to increase (as is seen in Fig. 4); at some length L , the mass effect becomes important when Q_s approaches Q_0 . At this juncture, much of the incoming water is abstracted from the suction zone, resulting in significantly less flow on the bed.

Consequently, the momentum of the bed decreases, resulting in a reduction of the sediment transport rate. Therefore, the turning point as shown in Fig. 8 should occur due to the interplay between the velocity and mass effects. The same occurrence also should be present if V_s is allowed to increase indefinitely for given values of Q_0 and L . This is because very large V_s will similarly lead to large Q_s that may significantly reduce the flow rate on the bed. At this juncture, the reduced sediment transport rate likely will cause significant sediment deposition because the sediment particles transported from upstream are no longer able to continue their motion downstream due to large changes to the local flow condition. At the limiting condition, one may also hypothesize that if the flow rate is reduced to be equal to the critical flow rate needed for bed sediment entrainment, Q_c , the sediment transport rate will become zero because the applied bed shear stress is less than that needed for sediment entrainment. In summary, increasing L or V_s likely will have a similar effect because they both directly influence the effective flow rate on the bed.

In fact, the effect of suction zone length on sediment transport rate has been noticed by past researchers. Oldenziel and Brink (1974), who conducted their tests in a 4-m long suction zone in a 15-m long flume, found that suction decreased sediment transport rate. Willets and Drossos (1975), on the other hand, applied a short suction zone (0.125 m) in a 3.6 m long open channel flume and found that sediment transport rate increased with suction rate. Willets and Drossos (1975) were confused with the conflicting inferences deduced from their own results when compared with those of Oldenziel and Brink (1974). They surmised that the disparity was due to different suction zone lengths used and deduced that the grain transport rate would decrease in a long zone of uniform suction. However, based on the experimental results of Liu (2010) (with tests conducted in a 32 m long flume with a 2 m long suction zone, the data shows that sediment transport rate increases in the suction zone) and Rao *et al.* (2011) (with tests conducted in a 25 m long flume with a 15 m long suction zone, the data also shows that sediment transport rate increases in the suction zone), the grain transport rate did not decrease with this significantly larger length. On the contrary, the data in Fig. 4a and those in Liu (2010) and Rao *et al.* (2011) show that a larger suction zone length will lead to larger sediment transport rate when $V_s/U_0 = \text{const.}$

Then what could have caused the different conclusions obtained by different researchers shown in Table 1? Fig. 4b show that q_b increases marginally with Q_s before a certain critical value of Q_s/Q_0 . In other words, the effect of Q_s on q_b will only be apparent when the applied suction rate is large enough. The different values of Q_s/Q_0 used by Oldenziel and Brink (1974) and Willets and Drossos (1975) may be the cause of the different conclusions drawn by them. The former used small suction rates ($Q_s/Q_0 < 3\%$) while the latter used suction rates Q_s/Q_0 of 5% to 12.5%. The data in Table 2 and Fig. 4b shows that q_b is not sensitive to the change of Q_s/Q_0 when $Q_s/Q_0 < 5.6\%$ ($Q_s < 0.4 \text{ L/s}$). Furthermore, O'Donnell *et*

al. (2002) experimentally found that suction effect is marginal on sediment transport rate, which is probably because they applied a low Q_s/Q_0 .

The notion that Q_s/Q_0 rather than V_s/U_0 better correlates sediment transport rate not only have potential application in fluvial erosion, but also in the field of membrane science. Up to now, many researchers in the field of membrane research used flux per unit area ($= Q_s/A_m$, where A_m = membrane surface area) to study the performance of membrane (Field *et al.*, 1995; Li *et al.*, 1998, etc.), as it is widely believed that increasing flux per unit area beyond a certain threshold value would lead to membrane fouling or foulant accumulation on the membrane surface. It should be noted that closed-conduit flow subjected to suction resembles a cross-flow membrane system in many ways. Because the length of the membrane surface can be designed and varied in the manufacturing process, the effect of suction zone length should be incorporated into the design. Therefore, Q_s/Q_0 could be a better parameter as it is better related to the suction effect in the membrane treatment process.

4 Conclusions

Laboratory experiments were conducted in this study to explore how suction zone length affects the sediment transport rate in closed-conduit flows.

The experimental results show that suction zone length, like suction intensity in the form of V_s/U_0 , can influence sediment transport rate. Within a certain range of Q_s/Q_0 , sediment transport rate increases with increasingly larger suction zone length for the same V_s/U_0 . Combining the effect of V_s/U_0 and suction zone length, the study shows that suction intensity in the form of Q_s/Q_0 is a superior variable to use in the analysis of sediment transport rate. Moreover, a new modified Froude number, Ω_{Q_s} , which accounts for the effect of Q_s rather than V_s , is developed and comparison of the data in the present study and that by Liu (2010) verifies the hypothesis that Q_s/Q_0 is better correlated to q_b than V_s/U_0 . Finally, PIV measurement of the velocity profile shows that the streamwise velocity in the very near-bed region increases with increasing V_s/U_0 at fixed L/h and also with increasing L/h at fixed V_s/U_0 , which is used to explain how suction zone length affects sediment transport rate.

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382 **Notations**

- 383 A = cross area of the closed conduit (m^2)
- 384 A_m = area of the membrane surface (m^2)
- 385 b = width of the closed conduit (m)
- 386 dA = area of a grid in vector field (m^2)
- 387 d_s = scour depth (m)
- 388 d_{50} = median grain size (m)
- 389 D_H = hydraulic diameter = $\frac{4A}{P}$ (m)
- 390 g = acceleration of gravitation (ms^{-2})
- 391 K = hydraulic conductivity (ms^{-1})
- 392 L = suction zone length (m)
- 393 M_0 = approach flow momentum, $M_0 = \rho \times Q_0 \times U_0 = \rho \times U_0^2 \times bh$ (kg.ms^{-2})
- 394 M' = approach flow momentum in the presence of suction, $M' = \rho \times Q_0' \times U_0' = \rho \times (U_0 - V_s \cdot L$
- 395 $/h)^2 \times bh$ (kg.ms^{-2})
- 396 M_t = momentum transfer across the sand bed, $M_t = \rho \times V_s^2 \times Lh$ (kg.ms^{-2})
- 397 n = porosity (-)
- 398 P = perimeter of the closed conduit (m)
- 399 q = flux of each grid element, $q = \left| \partial u / \partial x + \partial v / \partial y \right| dA$ ($\text{m}^2 \text{s}^{-1}$)
- 400 q_b = volumetric sediment transport rate per unit width with seepage ($\text{m}^2 \text{s}^{-1}$)
- 401 q_{b0} = volumetric sediment transport rate per unit width without seepage ($\text{m}^2 \text{s}^{-1}$)
- 402 Q_0 = undisturbed approach flow rate ($\text{m}^3 \text{s}^{-1}$)
- 403 Q_0' = effective approach flow rate Q_0' , $Q_0' = Q_0 - V_s \cdot L \cdot b$ ($\text{m}^3 \text{s}^{-1}$)
- 404 Q_c = critical flow rate needed for bed sediment entrainment ($\text{m}^3 \text{s}^{-1}$)
- 405 Q_s = suction flow rate ($\text{m}^3 \text{s}^{-1}$)
- 406 R = Reynolds number, $= \frac{U_0 D_H}{\nu}$ (-)
- 407 S_s = specific gravity, the ratio between the densities of sand and water (-)
- 408 u = horizontal velocity (ms^{-1})

- 409 u_{*0} = shear velocity without suction (ms^{-1})
- 410 u_{*0c} = critical shear velocity without suction (ms^{-1})
- 411 U_0 = mean flow velocity, $U_0 = Q_0/(b.h)$ (ms^{-1})
- 412 ν = vertical velocity (ms^{-1})
- 413 V_s = seepage velocity, $V_s = Q_s/(b.L)$ (ms^{-1})
- 414 ν = kinematic viscosity of water (m^2s^{-1})
- 415 τ_{*0} = shield's parameter which describes the initial condition of sediment bed before
- 416 seepage, $\tau_{*0} = \frac{u_{*0}^2}{(S_s - 1)d_{50}g}$ (-)
- 417 Φ = Einstein's parameter, $\Phi = \frac{q_b}{\sqrt{d_{50}^3 g (S_s - 1)}}$, which is defined as the dimensionless
- 418 volumetric sediment transport rate (-)
- 419 Ω_{Q_s} = a modified densimetric Froude number in the present study,
- 420 $\Omega_{Q_s} = \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{V_s}{K} \cdot \frac{L}{h} \right] d_{50}g} = \frac{U_0^2}{\left[(S_s - 1)(1 - n) - \frac{Q_s}{Q_0} \cdot \frac{U_0}{K} \right] d_{50}g}$ (-)
- 421 Ω_{V_s} = a modified densimetric Froude number in Liu (2010),
- 422 $\Omega_{V_s} = \frac{U_0^2}{\left[(S_s - 1)(1 - n) - V_s / K \right] d_{50}g}$ (-)
- 423
- 424

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492 Table 1 Summary of results of previous studies on suction effects on sediment transport

Source	Flume dimensions		d_{50} of sand (mm)	Parameter used for analysis	Sediment transport rate
	Length (m)	Seepage zone (m)			
Oldenzien and Brink (1974)	15	4	0.13, 0.22, 0.38, 0.57	V_s	Decrease
Willems and Drossos (1975)	3.6	0.125	0.73, 1.03, 1.3	Q_s	Increase
Rao and Nagaraj (1999)	3.6	2.4	0.32-3	V_s	Increase
O'Donnell <i>et al.</i> (2002)	10	0.36	0.13-0.57	V_s	Little effect
Lu and Chiew (2007)	30	2	0.9, 1.41, 1.64	V_s	Increase
Francalanci <i>et al.</i> (2008)	15	1.1	0.84	Q_s	Decrease
Liu (2010)	32	0.5, 1, 2	0.48, 0.9	V_s	Increase
Rao <i>et al.</i> (2011)	25	16	0.56	V_s	Increase
Liu and Chiew (2012)	32	2	0.48, 0.9	V_s	Increase
Cao and Chiew (2014)	9	0.5	0.84	V_s	Increase

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494

495 Table 2 Test conditions and experimental data ($Q_0 = 7 \text{ L/s}$, $u_{*0}/u_{*0c} = 0.997$)

Test Number (Series A)	Suction zone length (m)	Suction rate, $Q_s (\text{L s}^{-2})$	Suction velocity, $V_s (\text{ms}^{-1})$	Bedload transport rate, $q_b (10^{-6} \text{ m}^2 \text{ s}^{-1})$
(1)	(2)	(3)	(4)	(5)
A-1	0.5	0.000	0.0000	0.0011
A-2	0.5	0.150	0.0010	0.0011
A-3	0.5	0.294	0.0020	0.0008
A-4	0.5	0.400	0.0027	0.0030
A-5	0.5	0.563	0.0038	0.0038
A-6	0.5	0.670	0.0045	0.0046
A-7	0.5	0.810	0.0054	0.0280
A-8	0.5	0.960	0.0064	0.0631
A-9	0.5	1.200	0.0080	0.2012
B-1	0.2	0.000	0.0000	0.0003
B-2	0.2	0.120	0.0020	0.0005
B-3	0.2	0.256	0.0043	0.0006
B-4	0.2	0.380	0.0063	0.0016
B-5	0.2	0.486	0.0081	0.0025
B-6	0.2	0.610	0.0102	0.0050
B-7	0.2	0.840	0.0140	0.0263
B-8	0.2	0.950	0.0158	0.0505
B-9	0.2	1.100	0.0183	0.0764
C-1	0.1	0.000	0.0000	0.0009
C-2	0.1	0.130	0.0043	0.0008
C-3	0.1	0.294	0.0098	0.0009
C-4	0.1	0.352	0.0117	0.0012
C-5	0.1	0.420	0.0140	0.0017

C-6	0.1	0.550	0.0183	0.0052
C-7	0.1	0.670	0.0223	0.0102
C-8	0.1	0.800	0.0267	0.0163
C-9	0.1	0.930	0.0310	0.0305

Note: The data with test number starting from A, B and C are from the first, second and third series, respectively. The data in columns 2, 3 and 5 are measured directly, while V_s is calculated by $V_s = Q_s/A_s$. The Reynolds number R for all the experiments is 35481, which shows the flow is turbulent, where R

$$= \frac{U_0 D_H}{\nu}; \nu = \text{kinematic viscosity}; D_H \text{ is the hydraulic diameter, and } D_H = \frac{4A}{P}.$$

Figure 1 Schematic drawing of closed conduit (All units in meters, not to scale)

Figure 2 Schematic drawing of shortened suction zone (suction zone length = 0.2 m) (All units in meters, not to scale)

Figure 3 Schematic diagram of experimental setup for the measurements of axial (u) velocity:
(a) top view; (b) side view

513

514 Figure 4 Dimensionless volumetric sediment transport rate, Φ plotted against (a) V_s/U_0 ; (b)

515 Q_s/Q_0 in closed-conduit flow

516

517 Figure 5 Φ as a function of (a) Ω_{V_s} ; (b) Ω_{Q_s} (Note: 0.997, 0.98, 1.05, 1.08 and 1.16 denote

518 the value of $\frac{u_{*0}}{u_{*0c}}$, while the rest of the data denote the value of L/h in Fig .5a. They are

519 written only in forms of number due to space constraint)

520

Figure 6 Horizontal velocity profiles in the near-bed region under different V_s/U_0 at $x = 25$ cm

Figure 7 Horizontal velocity profiles in the near-bed region at different horizontal distance from the leading edge of the suction zone

528

529 Figure 8 Effect of suction zone length, L on q_b when L becomes infinitely large

530