Proceedings of the
International Conference on Mechanical Engineering 2011
(ICME2011) 18-20 December 2011, Dhaka, Bangladesh

ICME11-FL-017

EFFECTS OF THE INTRODUCTION OF SEEPAGE ON THE BED STABILITY AND TURBULENCE CHARACTERISTICS IN AN OPEN CHANNEL FLOW

Md Abdullah Al Faruque[1] and Ram Balachandar[2]

[1]Civil Engineering Technology, Rochester Institute of Technology, NY 14623, USA.
[2]Faculty of Engineering, University of Windsor, 401 Sunset Ave., Windsor, ON, Canada.

ABSTRACT
A comprehensive study was carried out to understand the effects of seepage on the turbulence characteristics of flow in an open channel. To this end, both suction and injection seepage tests were conducted covering a range of seepage rates. The tests were conducted at two different flow rates (450 GPM and 720 GPM) corresponding to Reynolds number 31,000 and 47,500 respectively. The variables of interest include the mean velocity, turbulence intensity, Reynolds shear stress, shear stress correlation and higher-order moments. It was seen that the seepage causes a significant change in mean velocity profile and the magnitude of this change depends on the seepage rate. Seepage also affects bed stability with injection increases the bed stability, whereas suction causes a reduction. The results show that the effect of seepage on velocity and turbulence characteristics is not restricted to the near-bed region but can be seen throughout the flow depth.

Keywords: Seepage, Turbulence, Open Channel flow.

1. INTRODUCTION
Natural channels, rivers, and streams have beds formed by earthen permeable material and experience seepage flow through boundaries due to the difference between water levels in the channel and the adjoining ground-water level. If the free water surface in the channel is higher than the adjoining ground-water level, seepage flow occurs out of the channel and is called ‘suction’. Whereas, if the free water surface in the channel is lower than the adjoining ground-water level, seepage flow occurs into the channel and is called ‘injection’. It has been noted that the hydrodynamic characteristics of a channel flow can be significantly altered by seepage flow [1]. Although, in most cases, the magnitude of seepage flow is much less in comparison to the main flow, in certain cases the inflow seepage can be large enough to produce a ‘quick’ condition in the channel bed or the outflow seepage can be large enough to cause a loss of water of as high as 45% of the water supplied at the upstream section of a channel [2]. In comparison with the number of studies on the turbulent flows over impervious smooth and rough boundaries, very few studies about the interaction of the pervious bed and the turbulent flow have been carried out.

The permeable boundary enables mass and momentum transfer across the interface between the fluid and the porous media, which needs to be accounted for in modeling such flows. The interaction between turbulent flow and a permeable boundary may result in changes in the velocity profile, turbulence intensity and boundary shear stress, as compared with those in relation to an impermeable boundary [3]. The variable intensity of seepage flow may cause variation in flow properties. Furthermore, porous bed can work as a sink or source for harmful toxicants and fine sediments.

Seepage can alter the flow boundary conditions and eventually affect sediment transport and can change scouring action in channels. The knowledge of the flow structure over the seepage zone is required for accurate estimation of the boundary shear stress. The process of suction draws faster moving flow into contact with the bed for a bed-type river intake. This process of suction can cause local scour and the undesirable exposure of the intake structure due to increase in boundary shear stress [4]. Furthermore, excess sediment deposition can cause severe navigational problems and may need extensive dredging work to keep the flowing of goods through waterways uninterrupted.

2. PREVIOUS STUDIES
Previous studies of flow over a porous boundary are much less compared to the flow over non-porous boundary, and more importantly, the outcome of these studies is not unanimous. An excellent review of seepage

studies can be found in [5].

In an effort to study the influence of seepage on sediment motion, [6] studied the effect of seepage on the hydrodynamic drag and lift forces acting on a sediment particle. They concluded that injection inhibits the motion of bed particles, while suction enhances the motion. [1] studied the effects of seepage on the stability, mobility, and incipient motion of sand-bed particles. They noted that suction decreases the stability of bed particles and increases their mobility, whereas injection increases the stability of the particles when compared with no-seepage condition. [7] concluded that suction would tend to increase the effective weight of the bed particles and, therefore, increase the stability of the bed. Conversely, with injection, the effective weight of the bed particles decreases and thereby decreases the bed stability. [8] also stated that injection reduces the apparent weight of the sand particles and eventually their stability. [6] commented that the bed of an alluvial channel alters the flow configuration and modifies the velocity profile near the channel bed. They concluded that a decrease in velocity near the bed contributes to a lower drag force in the presence of injection and an increase in velocity near the bed contributes to a higher drag force due to suction. However, [9] noted that the mean channel velocity increased with injection. [10] found a more uniform velocity distribution due to the increase in the near bed velocity and a reduction of velocity near the water surface subjected to bed suction.

[6] noted that in the presence of suction, there is a decrease in turbulence level, which eventually leads to lesser momentum exchange between fluid particles. In the presence of injection, they noted an increase in turbulence level, which eventually leads to a greater momentum exchange between fluid particles. They noted that turbulence fluctuations were more intense for injection than for suction or without seepage. [11] showed a considerable reduction in turbulence level and Reynolds stress with increasing suction rates. He commented that high suction rates tend to destroy the turbulence and there would be a probability of an inverse transition in the case of a long suction region. [12] also found similar reduction of turbulence intensities and Reynolds shear stress due to suction and noted that the reduction is more significant with higher relative suction. They recognized that over the entire water depth, turbulence intensities and Reynolds shear stress decrease more rapidly near the bed than those near the free surface.

One can summarize from above mentioned discussion that seepage influences the velocity distribution and potentially change the bed formation in the channel. There are conflicting reports about the effect of seepage on bed stability. The present study was carried out to understand the effect of the introduction of seepage on different turbulent characteristics in an open channel flow. Test results with various degrees of suction and injection are presented and discussed to understand the extent of influence of seepage in the depth-wise direction at two different channel flow rates. Particular attention is paid to mean velocity, turbulence intensity, Reynolds shear stress, shear stress correlation, higher-order moments and quadrant analysis to address the above mentioned issues from earlier researchers.

3. EXPERIMENTAL SETUP

Experiments were carried out in a 9-m long rectangular open channel flume (cross-section 1100 mm x 920 mm). The header tank upstream of the rectangular cross-section was 1.2 m square and 3.0 m deep. The nominal flow depth (d) was 100-mm, resulting in a width-to-depth ratio (b/d) of approximately 11. This value of the aspect ratio can be considered to be large enough to minimize the effect of secondary currents and the flow can be considered to be nominally two-dimensional [13]. The flume is a permanent facility and the quality of flow has been confirmed in several previous studies [14]. Sand particles with a median grain diameter of 2.46 mm were used to create the test bed.

The seepage zone subjected to suction or injection is 2.4 m long, 125-mm deep and spans the entire width of flume. The seepage zone was designed to ensure uniform seepage velocity over the entire area. Fifteen identical perforated pipes were used to drain water into the flow field (injection) or out of the flow field (suction) uniformly. Two separate identical pumps with control valves were used to maintain the flow rate for suction/injection, which was monitored using a flow meter. The sand was placed on top of a filter net, which in turns, overlays a perforated plate. The use of filter net prevents the sediment particles from falling down. Water is allowed to seep through the perforated plate, filter net and sand layer to ensure uniform seepage flow within the granular materials.

Two different flow rates (450 GPM and 720 GPM) were used and the flow was maintained to be subcritical. All the measurements were conducted along the centreline of the channel to minimize secondary flow effects. Preliminary tests were conducted to ensure a fully developed flow condition. The summary of the test conditions are presented in Table 1.

A commercial two-component fibre-optic LDA system (Dantec Inc.) powered by a 300-mW Argon-Ion laser was used for the velocity measurements. This system has been used in several previous studies and details are avoided for brevity [14][15]. The optical elements include a Bragg cell, a 500-mm focusing lens and the beam spacing was 38 mm. 10,000 validated samples were acquired at each measurement location.

4. RESULTS AND DISCUSSION

4.1 Mean Velocity

The distributions of the streamwise component of the mean velocity in outer coordinates are shown in Figure 1. Maximum velocity (U_e) and flow depth (d) are used to non-dimensionalize the streamwise mean velocity (U) and the wall normal distance (y), respectively. For injection, one can note a decrease in velocity near the bed and an increase in velocity near the free surface in comparison to the no seepage condition as shown in the insets of Figure 1a. A similar observation of decrease in the near bed velocity was also made by [6] and related it to a lower drag force on the bed material. One can also note from Figure 1a that the reduction of the near bed velocity and the increment in the near free surface velocity, increases with the increase of injection rate. A similar streamwise mean velocity distribution was also observed for the higher flow rate [16], but the extent of respective reduction or increase in the velocity near the bed or near the free surface, is less than the variation observed with the lower flow rate.

Table 1: Summary of Test Conditions

Test	Flow condition	% Rate of Suction/Injection	Flow Rate
1	No Suction or injection	0	450 GPM
2	Suction	5	450 GPM
3		7	450 GPM
4		9	450 GPM
5		12	450 GPM
6		14	450 GPM
7	Injection	5	450 GPM
8		7	450 GPM
9		9	450 GPM
10		12	450 GPM
11		14	450 GPM
12	No Suction or injection	0	720 GPM
13	Suction	3	720 GPM
14		5	720 GPM
15		7	720 GPM
16		9	720 GPM
17	Injection	3	720 GPM
18		5	720 GPM
19		7	720 GPM
20		9	720 GPM

The distributions of the streamwise component of the mean velocity for suction conditions are shown in Figures 1b for the lower flow rate. One can note from Figures 1b that the velocity profiles become more uniform in comparison to no seepage condition due to an increase in velocity near the bed. The increased velocity in the near bed location causes the reduction in velocity near the free surface to satisfy the continuity considerations (inset of Figures 1b). A similar observation was also made by [10]. [6] related the increase in near bed velocity to cause a higher drag force on the bed material. One can also note from Figure 1b that the increment of the near bed velocity and the reduction in the near free surface velocity, increases with the increase of suction rate. Unlike injection, the effects of suction on streamwise mean velocity is very similar for both lower and higher flow rates [16].

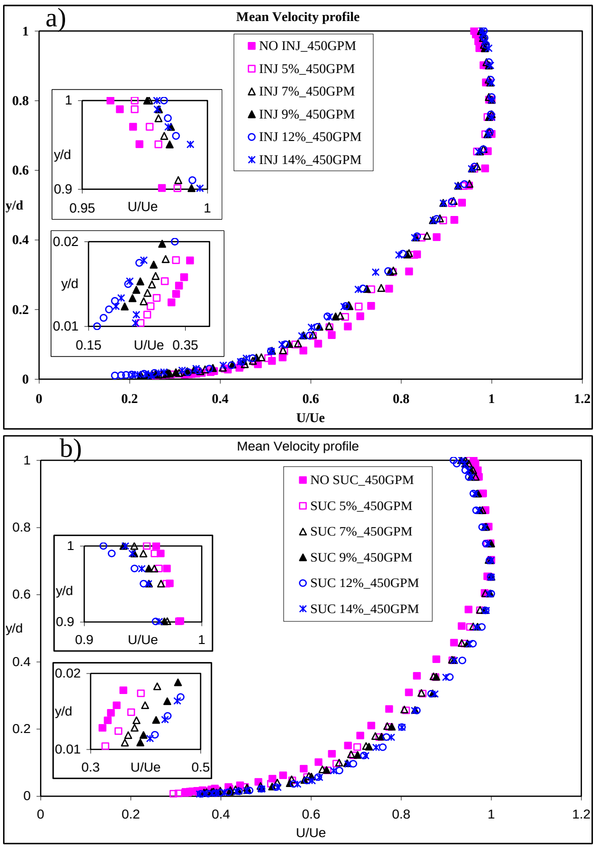

Fig 1. Mean velocity profile in outer coordinates for, a) Injection_450GPM, b) Suction_450GPM.

4.2 Turbulence intensity

Figure 2 shows the streamwise turbulence intensity for the lower flow rate in outer variables. Directly measured quantities like depth of flow and maximum velocity are used as the length and velocity scales, respectively, to reduce any additional uncertainties related to scaling parameters with computed quantities. One can note from Figure 2a that streamwise turbulence intensity attains a maximum value very close to the wall (y/d ~ 0.02) for all flow conditions. There is no significant effect of injection that can be observed from the bed up to the location of this peak. With the exception of the region very close to the bed, effect of injection is prevalent through most of the flow depth (0.05d ~ 0.8d). For this region, streamwise turbulence intensity increases with injection rate. For y/d > 0.8, the streamwise turbulence intensity reduces towards the free surface and attains a nearly constant value for all flow conditions. Similar streamwise turbulence intensity distribution can also be observed for the higher flow rate [16], but the increase in magnitude with increasing injection is much lower than those for lower flow rate. It can also be observed that the portion of constant streamwise turbulence tends to increase with increasing flow rates [16].

The variation of streamwise turbulence intensity for suction is shown in Figure 2b. Suction causes a reduction of streamwise turbulence intensity for most of the flow depth (0.05d ~ 0.75d). However, beyond y = 0.75d, an increase in the streamwise turbulence intensity can be seen up to the free surface, albeit small. Unlike injection, the effects of suction on streamwise turbulence intensity are very similar for both lower and higher flow rates [16].

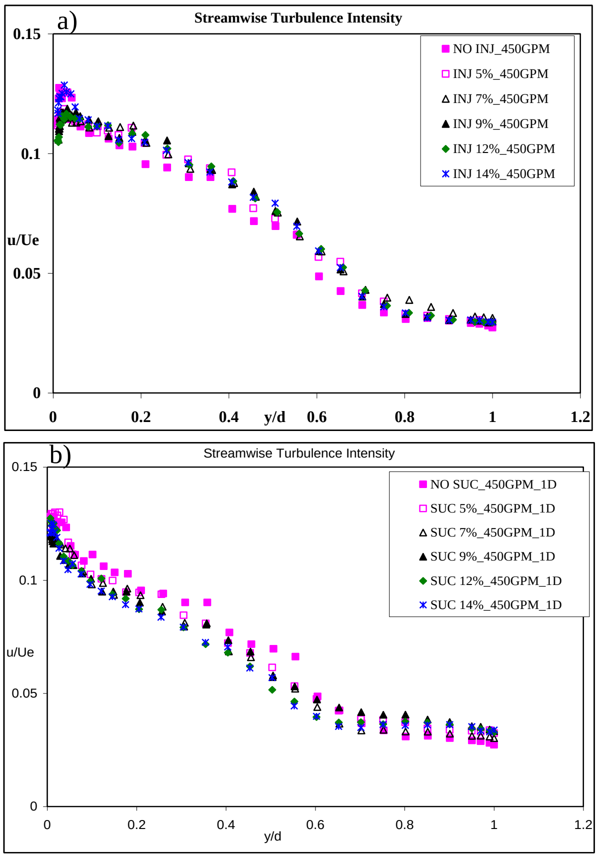

Fig 2. Streamwise turbulence intensity for,
a) Injection_450GPM, b) Suction_450GPM

Figure 3 shows the vertical turbulence intensity for the lower flow rate in outer variables. One can note from Figure 3a that vertical turbulence intensity increases with the introduction of injection in comparison to no seepage condition for most of the depth but the difference is less for higher flow rates [16]. On the other hand, Figure 3b shows a reduction of vertical turbulence intensity with suction in comparison to no seepage condition and the difference is very similar for both lower and higher flow rates [16]. Although the intensity of vertical turbulence is around 50% of the streamwise turbulence, this value can be a major contributing factor to mixing.

4.3 Reynolds shear stress

Figure 4 shows the Reynolds shear stress distribution in outer variables. For injection (Figure 4a), one can note an increase in Reynolds shear stress in comparison to no seepage condition for most of the depth. A similar distribution was also observed for the higher flow rate but the amount of increment and the affected region of flow depth is less than the variation observed with the lower flow rate [16]. One can see a reduction in Reynolds shear stress in comparison to the no seepage condition with the introduction of suction (Figures 4b) and the difference is distinctly visible for $y < 0.7d$. Unlike injection, the effects of suction on Reynolds shear stress are very similar for both lower and higher flow rates [16].

One can also note from Figure 4 that, near the free surface, the Reynolds shear stress reduces and becomes negative for all flow conditions above the location where dU/dy is negative.

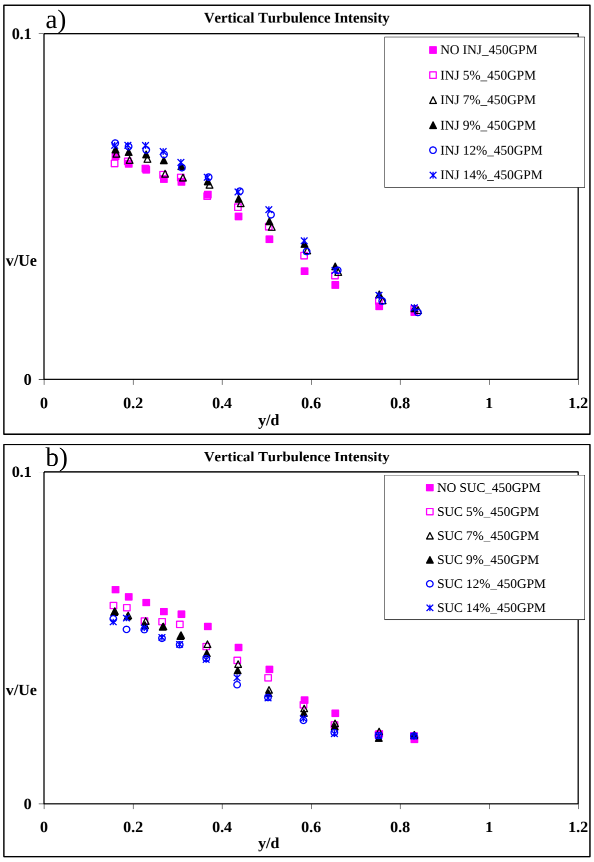

Fig 3. Vertical turbulence intensity for,
a) Injection_450GPM, b) Suction_450GPM

5. CONCLUSION

The main findings are summarized as follows:

a) Injection decreases the near-bed velocity causing the mean velocity profile to be less full compared to the no seepage condition. However, suction increases the near-bed velocity causing the mean velocity profile to become more uniform compared to the no seepage condition.

b) Injection results in an increase in bed stability, while suction reduces the bed stability.

c) Injection causes an increment of both streamwise and vertical turbulence intensity whereas suction reduces the values.

d) Reynolds shear stress increases with the introduction of injection for most of the depth, whereas suction reduces the Reynolds shear stress.

e) Effect of injection on mean velocity, turbulence intensity, Reynolds shear stress is found to be less significant for the higher flow rate.

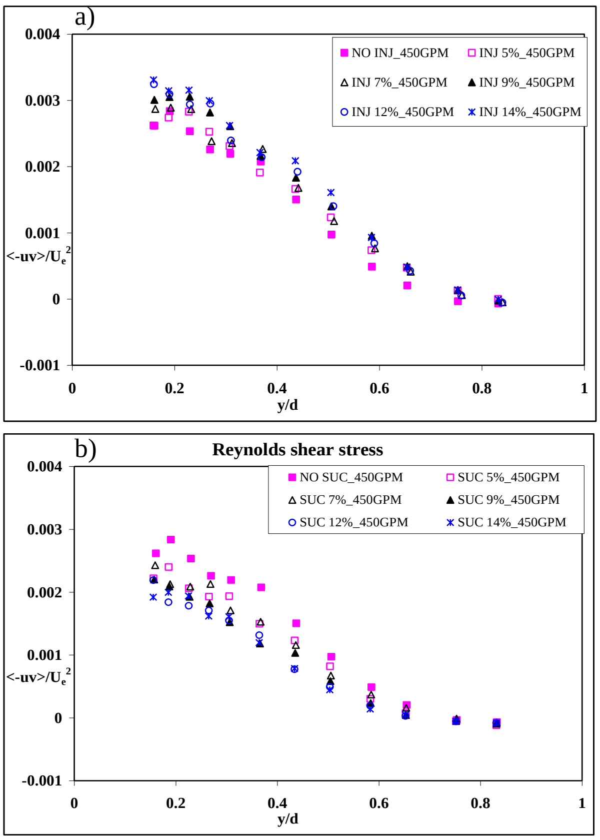

Fig 4. Reynolds shear stress for,
a) Injection_450GPM, b) Suction_450GPM.

6. REFERENCES

1. Rao, A. R., and Sitaram, N. (1999). "Stability and Mobility of Sand-Bed Channels Affected by Seepage." *Journal of Irrigation and Drainage Engineering*, 125(16), 370-379.
2. Shukla, M. K., and Mishra, G. C. (1994). "Canal discharge and seepage relationship." *Proceeding 6th National symposium on Hydro.* 263-274.
3. Cheng, N. S., and Chiew, Y. M. (1998). "Turbulent open-channel flow with upward seepage." *Journal of Hydraulic Research*, 36(3), 415-431.
4. Maclean, A. G. (1991). "Open channel velocity profiles over a zone of rapid infiltration." *Journal of Hydraulic Research*, 29(1), 15-27.
5. Lu, Y., Chiew, Y. M., and Cheng, N. S. (2008). "Review of seepage effects on turbulent open-channel flow and sediment entrainment." *Journal of Hydraulic Research*, 46(4), 476-488.
6. Watters, G. Z., and Rao, M. V. P. (1971). "Hydrodynamic effects of seepage on bed particles." J. Hydr. Div., ASCE, 101(3), 421-439.
7. Simons, D. B., and Richardson, E. V. (1966). "Resistance to flow in alluvial channels." *Geological Survey Prof. Paper, 422-J,* U.S. Geological Survey, Washington, D.C.
8. Oldenziel, D. M. and Brink, W. E. (1974). "Influence of suction and blowing on entrainment of sand particles." *Journal of the Hydraulic Division*, 100(HY7), 935-949.
9. Richardson, J. R., Abt, S. R., and Richardson, E. V. (1985). "Inflow seepage influence on straight alluvial channels." *Journal of Hydraulic Engineering*, 111(8), 1133-1147.
10. Chen, X., and Chiew, Y. M. (2004). "Velocity distribution of turbulent open-channel flow with bed suction." *Journal of Hydraulic Engineering*, 130(2), 140-148.
11. Prinos, P. (1995). "Bed-suction effects on structure of turbulent open-channel flow." *Journal of Hydraulic Engineering*, 121(5), 404-412.
12. Chen, X., and Chiew, Y. M. (2007). "Turbulence characteristics of open-channel flow with bed suction." *Journal of Engineering Mechanics*, 133(12), 1388-1393.
13. Nezu, I. (2005). "Open-channel flow turbulence and its research prospect in the 21st century." *Journal of Hydraulic Engineering*, 131(4), 229-246.
14. Faruque, M. A. A., Sarathi, P., and Balachandar, R. (2006). "Clear water local scour by submerged three-dimensional wall jets: Effect of tailwater depth." *Journal of Hydraulic Engineering*, 132(6), 575-580.
15. Afzal, B., Faruque, M. A. A., and Balachandar, R. (2009). "Effect of Reynolds number, near-wall perturbation and turbulence on smooth open channel flows." *Journal of Hydraulic Research*, 47(1), 66-81.
16. Faruque, M. A. A. (2009). "Smooth and rough wall open channel flow including effects of seepage and ice cover." PhD thesis, University of Windsor, Windsor, Canada.

7. NOMENCLATURE

Symbol	Meaning	Unit
d	Nominal flow depth	(mm)
U	Streamwise mean velocity	(m/s)
U_e	Maximum streamwise velocity	(m/s)
y	Wall normal distance	(mm)

9. MAILING ADDRESS

Md Abdullah Al Faruque
Rochester Institute of Technology,
Engineering, RMIT University
78 Lomb Memorial Drive, Rochester,
NY 14623, USA.
Telephone: 585 475 6664
Fax: 585 475 7964
E-mail: aafite@rit.edu