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Study of Flow Field Around Abutment Under Suction Seepage

Panchali Chakraborty, Abdul K. Barbhuiya

***Abstract:** The present study investigates the effects of side, vertical, and a combination of both side and vertical suction seepage on the flow patterns in a laboratory flume. To examine streamwise, transverse, and vertical components, an Acoustic Doppler Velocimeter (ADV) is used to analyze the complete velocity readings. The results demonstrate that near-bed velocity is relatively higher under suction seepage conditions than in other conditions. The impact of side suction seepage is primarily in the lower area next to the side wall. The vertical and transverse components of the flow mostly stay negative (downward and towards the wall). Combined suction seepage has a high velocity in the lower zone close to the side wall. Using velocity vector plots, it is observed how seepage affects wake and primary vortices, causing disruptions to the flow upstream and downstream of the abutment. These understandings are essential for creating hydraulic structures that are stable and long-lasting by better withstanding these flow dynamics.*

***Keywords:** Flow Velocity, Suction Seepage, Abutment, Seepage Velocity.*

Abbreviations:
ADV: Acoustic Doppler Velocimeter

Nomenclature

d_{50}: Median diameter of sediment particles;
d_e: Maximum scour depth,
σ_g: Geometric standard deviation
h: Approach flow depth
L: Abutment length
u,v,w: Time-averaged velocity components in (x, y, z)
x,y,z: Cartesian coordinates
z: Bed elevation
U: Approach flow velocity

I. INTRODUCTION

Natural rivers, banks, and artificial channels such as irrigation systems are commonly surrounded by sand, gravel, or other loose materials that allow water to flow through them. The flow of water, known as seepage, is determined by the interaction between groundwater and surface water levels.

When the groundwater level exceeds the water level in the river or channel, water seeps up from the ground into the stream; this process is known as upward seepage or injection. When the surface water level exceeds the groundwater level, water flows from the stream into the earth, and the occurrence is known as downward seepage or suction [1]. Though the seepage flow is minor compared to the river flow, it is very significant [10]. These small water movements can subtly impact how the river behaves and how the riverbed and banks evolve. In the past, engineers might have ignored seepage because it appeared insignificant, but it can have severe and unexpected effects [2]. The upward seepage can weaken the stability of sand and sediment on the river bed. If excessive water is pushed up, the sand particles on the riverbed may "boil" or rise, causing turbulence and instability [11]. This can cause riverbanks to deteriorate and collapse. In another case, the riverbed might become more stable during suction seepage (or downward seepage) [3]. This occurs because water seeps from the river into the ground, exerting additional pressure on the sediment and particles on the riverbed [12]. The water seeping raises the effective weight of the particles; this increased pressure helps to hold the sediment in place, lowering the risk of erosion or sediment transfer.

The flow field near abutments and piers during clear water scour has been widely studied [4]. While some research has investigated flow fields around piers under seepage conditions [5], to our knowledge, studies have yet to concentrate on the flow field surrounding abutments under seepage [6]. Previous studies have found that when water seeps through the boundary when suction occurs, the flow of a river or channel slows near the surface but increases closer to the riverbed [7]. When seepage occurs around a structure, the flow field on the riverbed may alter, so additional research is needed to determine how this downward seepage occurs in the presence of an abutment along the channel [8]. Gaining a better knowledge of this might be highly useful for engineers working in the field because it would assist them in regulating how water flows and sediment movement interact, preventing situations like erosion due to severe scour or unexpected changes in the river course [9]. Thus, the present paper aims to determine how the vertical and side suction seepage affects the flow distribution in regions where the river interacts with permeable boundaries in the presence of abutment, contributing to changes in the flow dynamics and stability of the riverbed.

II. EXPERIMENTAL SETUP AND PROCEDURE

Experiments were conducted in a rectangular steel flume 18.6 meters long, 0.9 meters wide, and 0.8 meters deep. The test segment was located in the center of the flume. Two side chambers measuring 3 m

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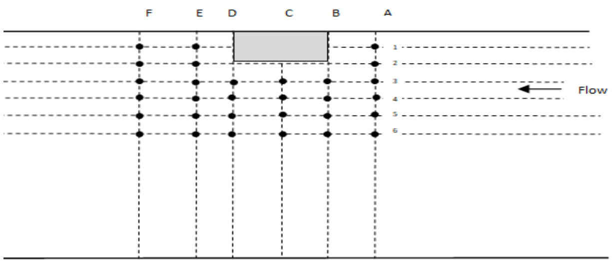
***Correspondence Author(s)**
Panchali Chakraborty*, Scholar, Department of Civil Engineering, National Institute of Technology, Silchar (Assam), India. Email ID: panchali_rs@civil.nits.ac.in. ORCID ID: 0000-0002-5169-575X
Prof. Abdul K. Barbhuiya, Department of Civil Engineering, National Institute of Technology, Silchar (Assam), India. Email ID: akbarbhuiya@yahoo.com

long, 0.3 m wide, and 0.5 m deep were connected to each side flume. The partition wall between the main and side chambers was made of perforated steel plates with 35% porosity. To arrest the silt produced by seepage flow, a perforated sheet was placed 5 cm above the bottom of the main chamber and extended to the whole length of the test section, including the side chambers. Similarly, vertical perforated sheets were positioned 5 cm away from the vertical wall of each side chamber. The test area was a seepage zone, with six holes evenly spaced and connected to a pipe network outfitted with suction and injection seepage valves. Similarly, the side chambers included three apertures on the sides and bottom walls for seepage flow.

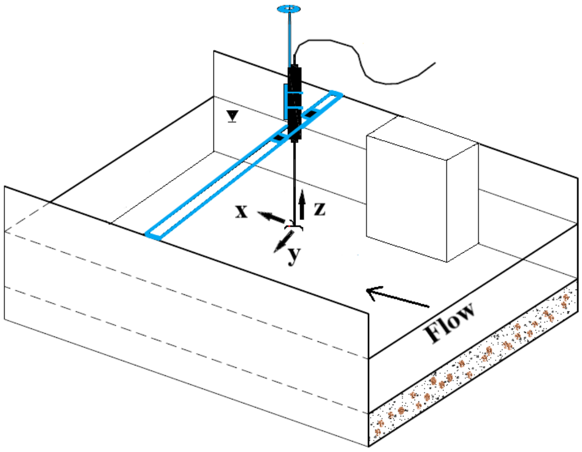
Initially, the abutment model was vertically positioned in the sediment bed, 125 cm upstream of the test section, and attached to one side wall of the flume with adhesive tape. Sediments were then put in the test section (d_{50} = 0.86mm) and the side chambers and levelled to keep the top level with the channel bed. The sediments used in the trials were glued along the channel upstream edge to keep the bed's roughness consistent. The sediment bed was carefully levelled with a wooden rammer, and the precision was confirmed using a spirit level. The final bed level was verified with a point gauge to guarantee uniformity, and water was pumped into the sediment recess.



[Fig.1: Observation Locations for Experiments with Abutment]

Two sets of experiments were performed. The first set of ADV data was collected with no seepage, and the second set measured the flow field under various suction seepage situations. The instantaneous 3D velocity components were measured using a SonTek 5 cm down-looking acoustic Doppler velocimeter (ADV). The ADV used the pulse-to-pulse coherent Doppler shift process, which generated three-dimensional velocity components at a frequency of 50 Hz. The acoustic sensor is made of one transmitting transducer and three receiving transducers, which are positioned 120° apart and coupled in short arms around the transmitter.

In the experiments with and without seepage, velocity measurements were taken at six sections (Figure 1): upstream of the abutment (A), along the line of the upstream nose of the abutment (B), at the face of the abutment (C), along the line of the downstream nose of the abutment (D), immediately downstream of abutment (E), and further downstream of abutment (F).In each portion, measurements were taken along six vertical lines (5cm, 10cm, 15cm, 20cm, 25cm, and 30cm from the side wall).



[Fig.2: Schematic Diagrams Showing the Sign Convention of the Velocity Measurements]

A schematic diagrams showing the sign convention of the velocity measurements are shown in Fig.2. Cartesian coordinates (x, y, z) express the abutment time-averaged velocity components (u, v, w). The average approaching flow velocity U and the transverse length of the abutment l, respectively, normalize all linear dimensions and velocity components. The flow fields are shown as planes at various vertical sections, where $\hat{y}$ is y/l and $\hat{z}$ is z/l. Furthermore, flow vectors are displayed at various horizontal sections at $z = 0.5d_e$ from the maximum scour depth level and $z = 0.33h$ from the free surface. This investigation does not cover the flow field close to the free surface because of ADV constraints, which prevent the probe from measuring velocity in the zone 5 cm below the free surface.

III. RESULT

A. Flow Field Around Abutment Without Seepage

i. Vertical Distributions

The vertical distributions of normalized time-averaged streamwise velocity (u/U) at different vertical sections are shown in Fig.3; from the figure, it is found that upstream of the abutment, the magnitude of streamwise velocity is less in the upper zone has a negative magnitude near the bed indicating flow reversal leading to the formation of primary vortex due to the presence of abutment. However, beyond the abutment line, the magnitude is a little more than the velocity of the upstream approach. In front of the upstream abutment nose, the velocity was a little less near the lower zone; however, as the distance from the abutment increases, the velocity achieves a parabolic distribution along the vertical, having maximum magnitude near the free surface. In front of the abutment (section c), the velocity distribution is almost uniform, having a maximum recorded value of 1.3U. In the downstream edge of the abutment, there was a slight fluctuation of the streamwise components along the vertical. At the downstream section, immediately behind the abutment, the streamwise velocity was negative with feeble magnitude; however, beyond the abutment line, the distribution was irregular.

Further downstream of the abutment, the streamwise component was also found to be irregular, having no

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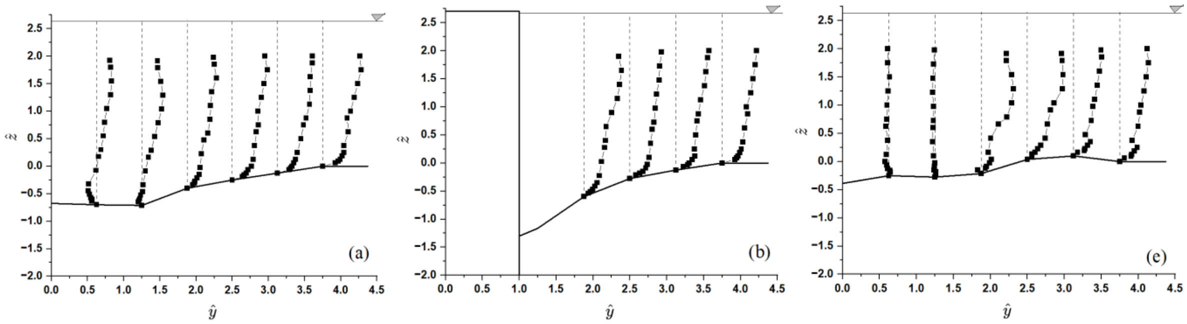
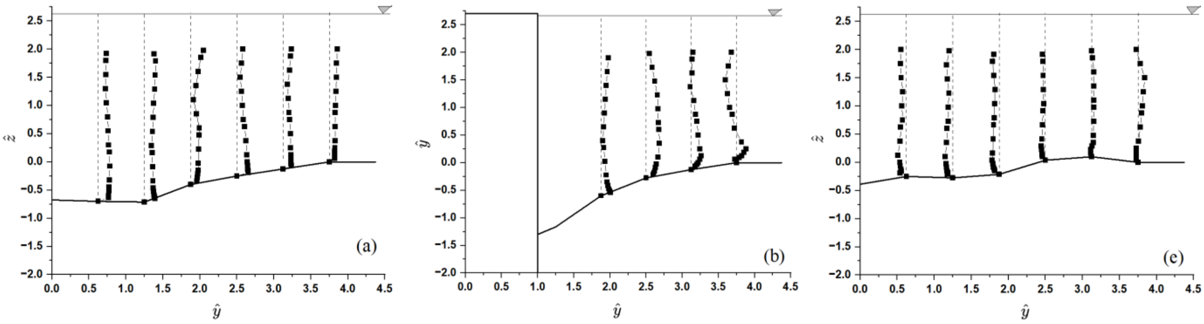
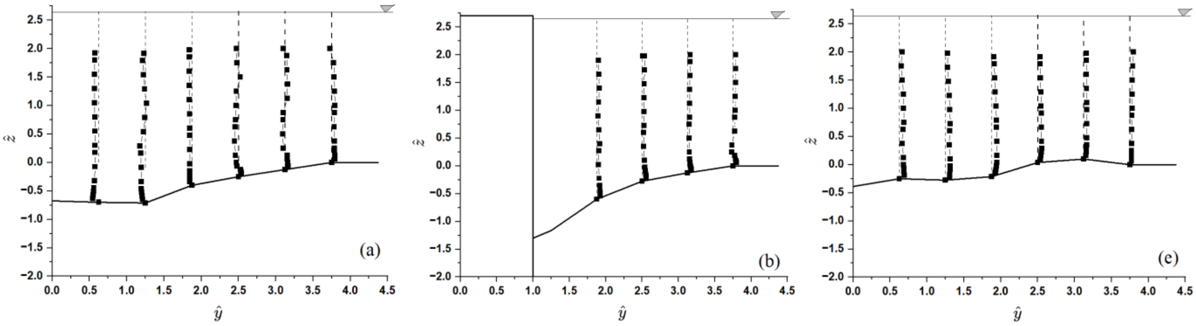
consistent trend, indicating the formation of a wake vortex. The transverse velocity (*v/U*) component (Fig.4) shows consistently positive values (flow away from the side wall) at the upstream section due to flow constriction with a measured maximum value of 0.27*U*. At the abutment nose and in front of the abutment, it mostly shows positive values due to the deflection by the abutment. In some locations, the negative value may be due to the flow separation at the upstream edge of the abutment. At the abutment nose and further downstream, the *v* component was found to be negative due to the effect of the wake vortex. The vertical velocity (*w/U*) component (Fig.5) in the upstream section shows negative values due to the pressure gradient, suggesting a downward flow tendency. Flow mainly exhibits positive values in the upstream nose and front of the abutment, indicating a predominant upward flow tendency due to flow separation. Around the downstream edge of the abutment, the flow is upward in the lower zone. In contrast, it is in a downward direction in the upper zone, probably due to the effect of the primary vortex. In the downstream section, vertical velocities were primarily positive with a few negative values, indicating an irregular flow pattern due to the formation of wake vortices.



[Fig.3: Vertical Profile of Streamwise Velocity (*u/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (c) of the Abutment for no Seepage Condition]



[Fig.4: Vertical Profile of Transverse Velocity (*v/u*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (e) of the Abutment for no Seepage Condition]



[Fig.5: Vertical Profile of Vertical Velocity (*w/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (e) of the Abutment for no Seepage Condition]

ii. Velocity Vectors

The normalised time-averaged velocity vectors at two horizontal planes at a distance of $z = 0.33h$ from the free surface and at $z = 0.5d_e$ from the maximum scour depth level are shown in Fig.6. The velocity vectors at $0.5d_e$ show the passage of flow within the scour hole, where the reverse flow due to the primary vortex upstream of the abutment, accelerated flow in front of the abutment, and wake vortex downstream of the abutment is depicted. At $0.33h$, the flow magnitude upstream of the abutment is less due to the presence of the abutment. The flow accelerated before the abutment and attained a maximum velocity of $1.31U$. At the downstream of the abutment, mild reverse flow reflects the development of the wake vortex behind the abutment. However, the flow regains downstream and becomes almost similar to the undisturbed flow. Generally, flow is more influenced in the lower zone due to the presence of abutment.

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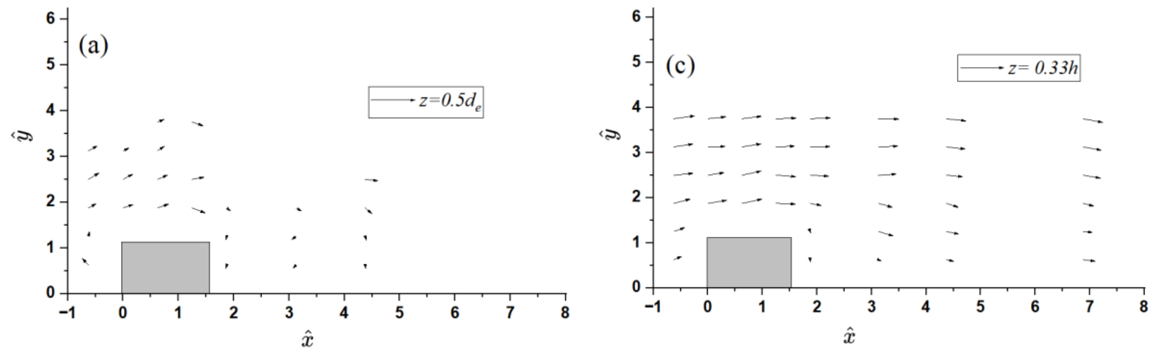

[Fig.6: Normalised Velocity Vectors at Horizontal Sections for Abutment with no Seepage z = (a) *0.5de* and (b) *0.33h*]

B. Flow Field Around Abutment with Suction Seepage

i. Velocity Distribution

- *Vertical Suction with Abutment*

The streamwise velocity (*u/U*), transverse velocity (*v/U*), and vertical velocity (*w/U*) components are represented in Fig.7 - Fig.9, respectively. The influence of vertical suction is mainly observed near the bed. In the upstream of the abutment, the magnitude of the harmful component is less compared to the condition of no seepage. These affect the formation of a primary vortex, which usually develops upstream of the abutment. The suction seepage dampens the primary vortex, resulting in less scour. In the upstream section of the abutment, the velocity near the bed shows a negative value, indicating reversal flow. In front of the abutment near the bed, velocity increased; however, in the upper flow zone, the influence of suction is not observed. Similarly, downstream of the abutment, the velocity was higher in the lower zone of the flow due to vertical suction seepage with negligible influence in the upper zone. Like the streamwise component, the transverse component *v*, upstream of the abutment, is influenced by the suction seepage. The dominant feature of the positive transverse component near the bed, which is the typical character of the flow upstream of the abutment, is reduced due to the influence of suction seepage. In front of the abutment, the transverse velocity distribution is similar to that of a no-seepage condition, depicting vortex shedding influence along the downstream edge of the abutment. The negative value of the *v* component near the bed due to wake formation is also less due to suction seepage. There is not much effect in the *w* component due to vertical suction seepage. Generally, a small negative value of the w component indicates mild downflow with a minor magnitude near the bed at the upstream and in front of the abutment.

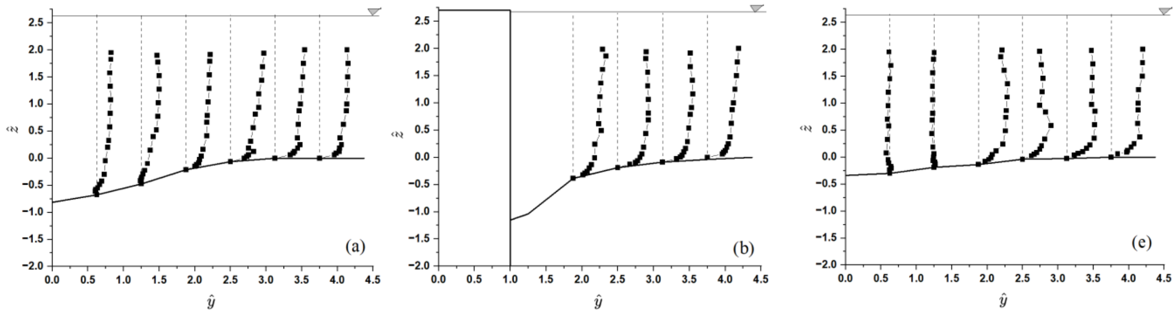

Fig.7: Vertical Profile of Streamwise Velocity (*u/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (e) of the Abutment in the Presence of Vertical Suction Seepage]

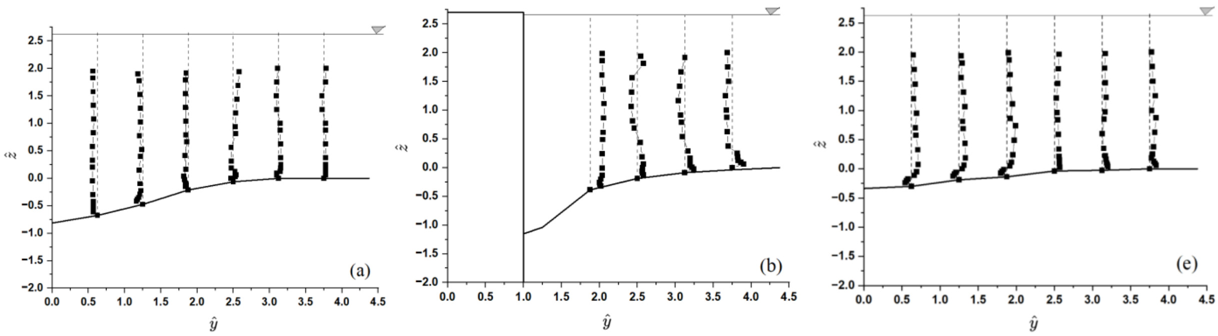

Fig.8: Vertical Profile of Transverse Velocity (*v/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (c) of the Abutment in the Presence of Vertical Suction Seepage]

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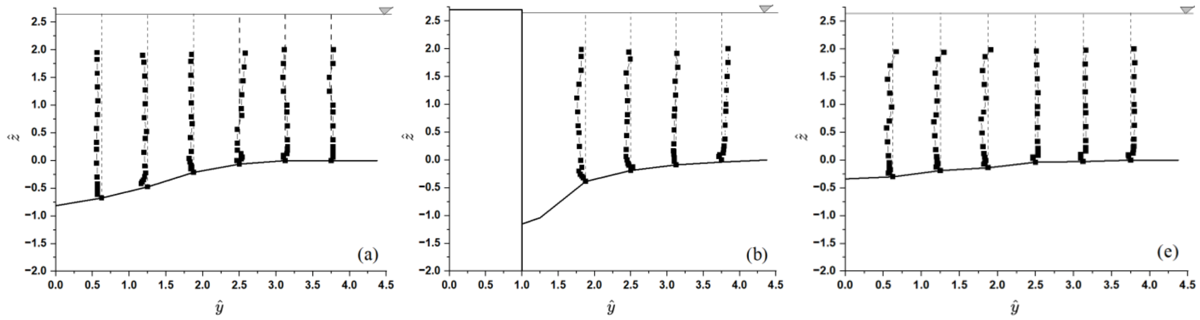
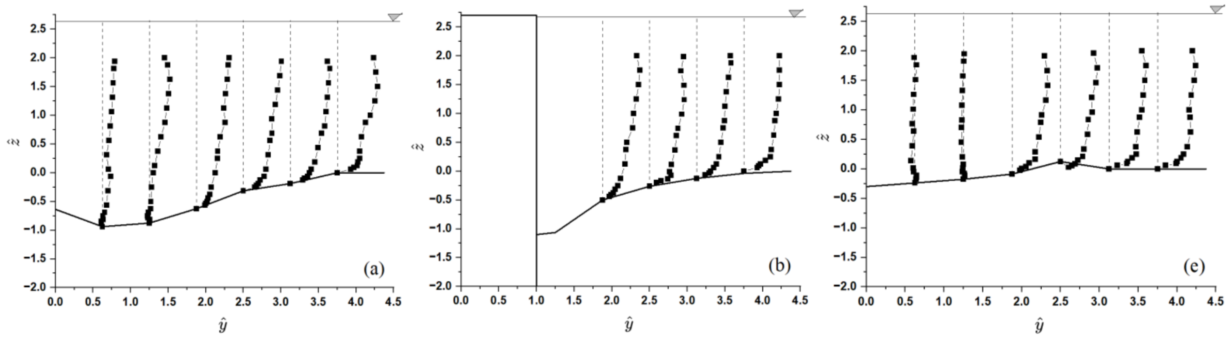


[Fig.9: Vertical Profile of Vertical Velocity (*w/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (e) of the Abutment in the Presence of Vertical Suction Seepage]

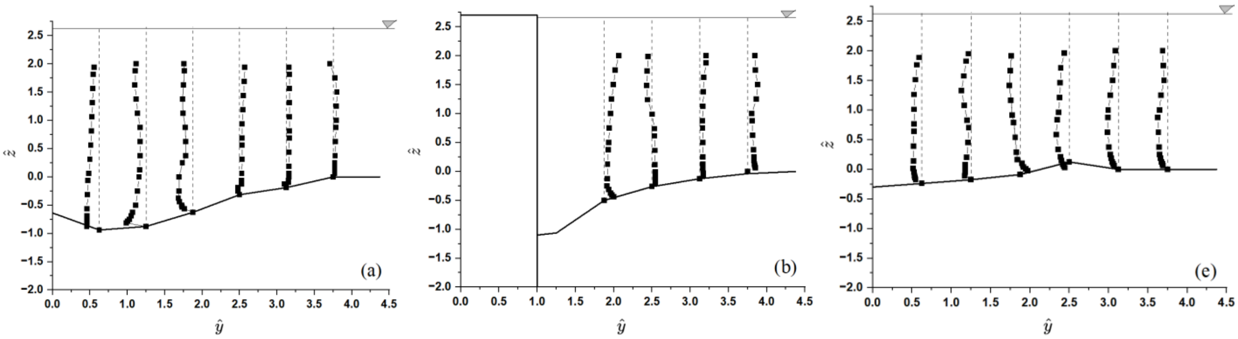
In the downstream section, the *w* component is mainly positive due to the wake vortex's influence on the upper flow zone. With some exceptions, a slight downward flow (negative value) is observed near the bed, possibly due to the undulated bed form.

- *Side Suction with Abutment*

The vertical distribution of streamwise velocity (*u/U*), transverse velocity (*v/U*), and vertical velocity (*w/U*) components is represented in Fig.10 to Fig.12, respectively. Figure 10 shows that at the upstream of the abutment, side suction strongly influences the streamwise component near the side wall, mainly in the lower flow zone. The magnitude of the *u* component is found to be very small, and the feature of the primary vortex is not noticed. Side suction seepage has little influence in front of the abutment. The downstream of the abutment u component is very feeble immediately behind the abutment, and the flow is regained as it moves further downstream. The dominant feature of the transverse velocity component (*v/U*) upstream of the abutment in the lower flow zone is observed due to the side suction seepage. A higher negative magnitude in the lower flow zone indicates the flow release through side suction seepage. No apparent influence on the *v* component is observed in front of the abutment. In the downstream section, the negative value generally reflects the impact of side suction. A positive value of the v component is observed at some locations due to vortex shedding. Similar to the *u* and *v* components, the *w* component also affects the upstream and downstream of the abutment near the side wall due to suction seepage. Negative values of the *w* component in these zones are due to the flow release through suction seepage.



[Fig.10: Vertical Profile of Streamwise Velocity (*u/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (e) of the Abutment in the Presence of Vertical Suction Seepage]



[Fig.11: Vertical Profile of Transverse Velocity (*v/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (e) of the Abutment in the Presence of Side Suction Seepage]

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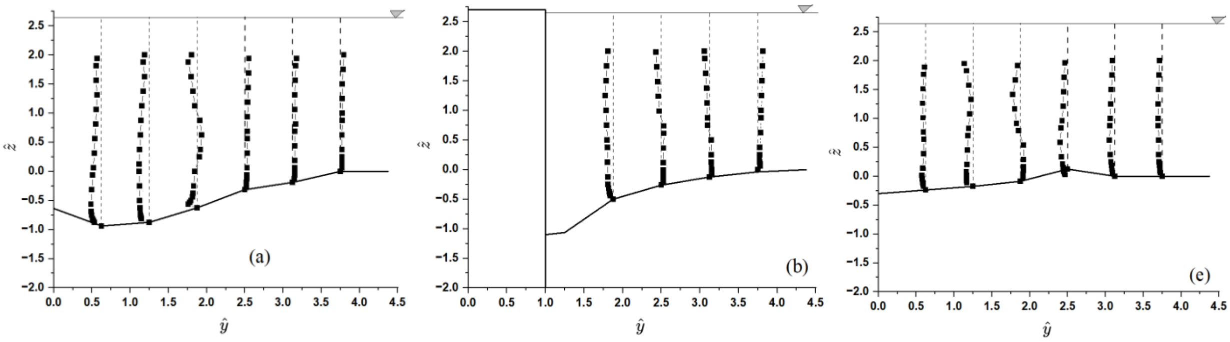


[Fig.12: Vertical Profile of Vertical Velocity (*w/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (e) of the Abutment in the Presence of Side Suction Seepage]

- *Combined Suction with Abutment*

Fig. 13 presents the streamwise velocity (u/U). The figure shows that upstream of the abutment, the magnitude of the *u* component is small, and the traces of the primary vortex are minimal. In the front and downstream of the abutment, the near-bed velocity is higher compared to the no-seepage condition. At the downstream section immediately behind the abutment, the *u* component is weak, and the flow is regained as it moves further downstream.

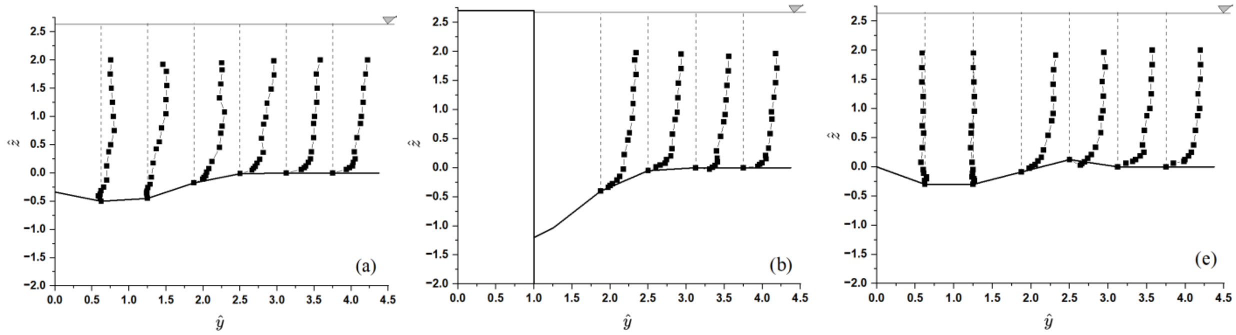
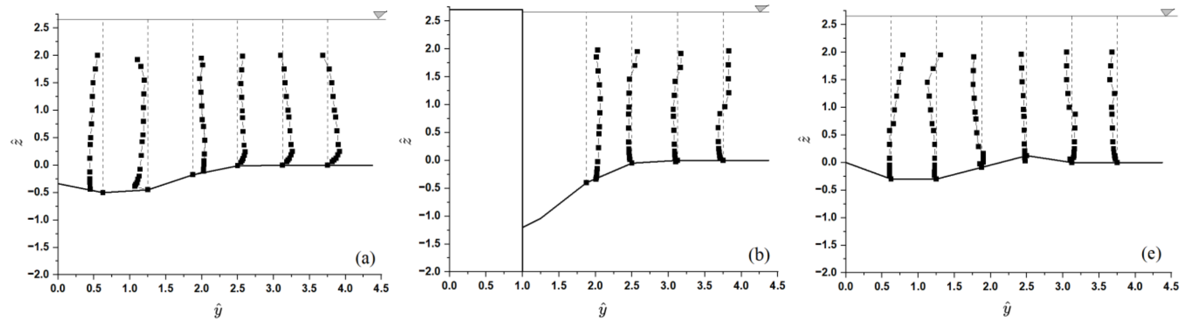
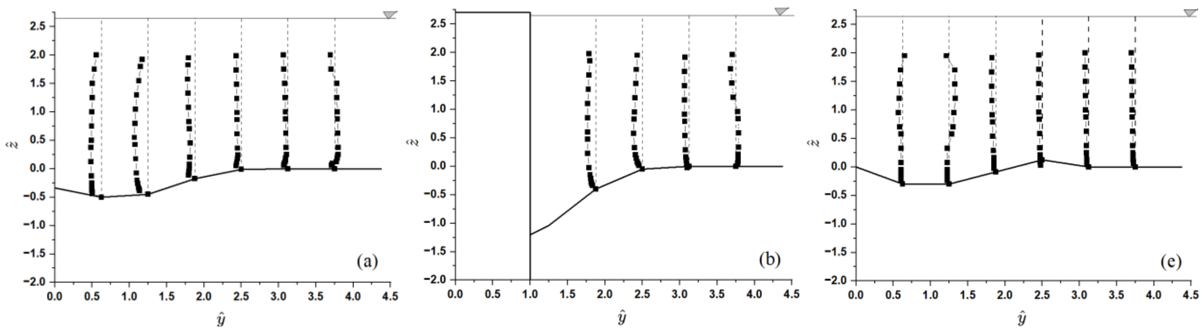


Fig.13: Vertical Profile of Streamwise Velocity (*u/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (e) of the Abutment in the Presence of Combined Suction Seepage.



[Fig.14: Vertical Profile of Transverse Velocity (*v/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (e) of the Abutment in the Presence of Combined Suction Seepage]



[Fig.15: Vertical Profile of Vertical Velocity (*w/U*) at Upstream Section (a), Upstream Nose (b), and Downstream Section (e) of the Abutment in the Presence of Combined Suction Seepage]

The transverse velocity (*v/U*) and vertical velocity (*w/U*) components are represented in Fig. 14 and Fig. 15, respectively. Upstream of the abutment, the transverse velocity component in the lower flow zone shows a dominant effect of combined suction seepage. Near the side wall, the higher negative magnitude in the lower flow

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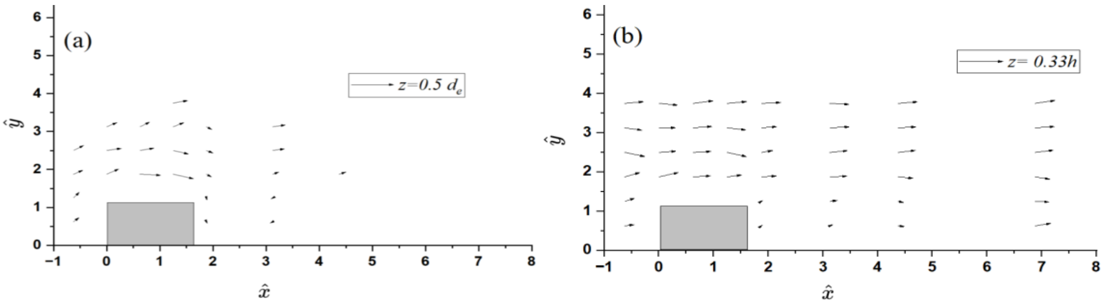
zone indicates the flow release through side suction seepage. In contrast, away from the wall, the magnitude of flow is affected by vertical suction seepage. No visible influence on the *v* component is observed in front of the abutment. The negative values near the side wall at the downstream section reflect the side suction effect. The positive value of the *v* component near the bed is observed due to vortex shedding occurring on the combined efforts of vertical suction and main flow. Similarly, the *w* component is also affected upstream and downstream of the abutment near the side wall due to side suction seepage. The effect near the side wall is comparatively more upstream of the abutment, while away from the wall, the effect is less observed in the middle of the test section. Negative values of the *w* component in these zones are due to the flow release through suction seepage.

ii. Velocity Vector

- *Vertical Suction with Abutment*

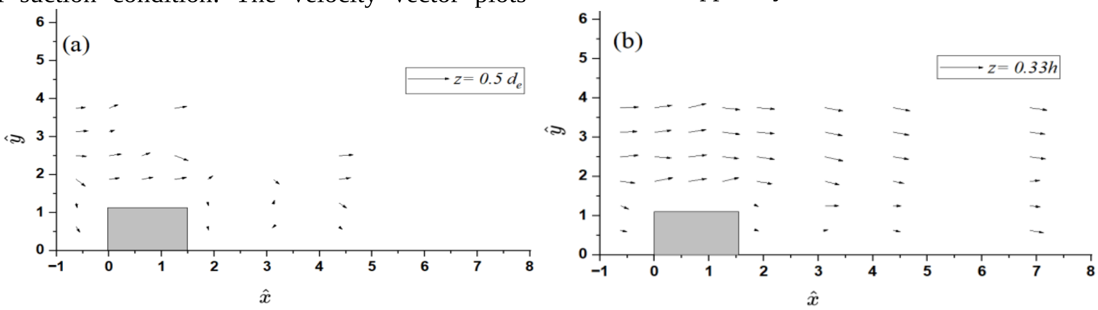
Figure 16 gives the velocity vectors at horizontal planes of 0.33h from the water surface and 0.5de from the maximum scour level with vertical suction seepage. The effect of suction seepage is found near the bed only in higher velocity compared to other flow conditions. The vector plot represents a standard flow pattern around an obstruction at another depth level.



[Fig.16: Normalized Velocity Vectors at Horizontal Sections for Abutment with Vertical Suction Seepage *z* = (a) *0.5de*, and (b) *0.33h*]

- *Side Suction with Abutment*

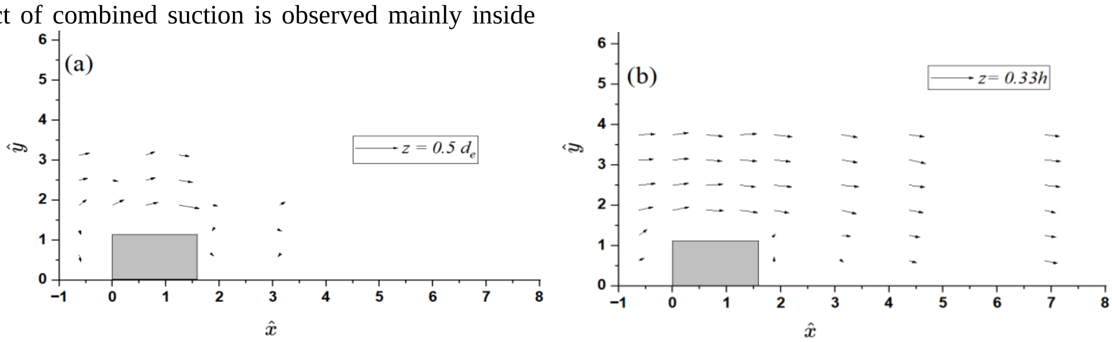
Figure 17 presents the velocity vector under the side suction condition for all three horizontal planes, similar to the vertical suction condition. The velocity vector plots clearly show the influence of side suction on the main flow. The flow is attracted towards the side wall. It is more prominent inside the scour hole; however, its effect is also seen in the upper layer of flow.



[Fig.17: Normalized Velocity Vectors at Horizontal Sections for Abutment with side Suction Seepage *z* = (a) *0.5de*, and (b) *0.33h*]

- *Combined Suction with Abutment*

Figure 18 shows the velocity vectors at two horizontal planes under combined vertical and side suction conditions. The impact of combined suction is observed mainly inside the scour hole. The flow is attracted into the scour hole, and the near-bed velocity magnitude is also higher than in other flow conditions.



[Fig.18: Normalized Velocity Vectors at Horizontal Sections for Abutment with Combined Suction Seepage *z* = (a) *0.5de*, and (b) *0.33h*]

IV. CONCLUSION

Based on the results of the present investigation, the following conclusions can be derived:

1. Suction seepage condition causes comparatively higher near-bed velocity than no suction seepage condition seepage and injection seepage conditions.
2. Vertical suction increases

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the streamwise velocity component near the bed compared to the condition of no seepage. The magnitude of the transverse element diminishes, and the vertical component increases in the downward direction due to vertical suction. Side suction seepage mainly affects the lower zone near the side wall. The transverse and vertical components of flow mostly remain negative (towards the wall and downward). Combined suction seepage has high velocity in the lower zone near the side wall. The transverse and vertical components of flow move towards the side wall and downward, respectively.

3. In the presence of an abutment, the vertical, side, and combined suction influence the streamwise component and increase the magnitude by 21.19%, 9.13%, and 7.64 %, respectively. The velocity study indicates that the location of maximum velocity near the bed is closer to the abutment front face for all suction conditions.

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DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted with objectivity and without any external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The article's resources are not publicly accessible. Credential required for data access and material availability statement. Facilitate access to the data in cases where it is not publicly accessible. The data and materials used in this study are not publicly available. They can be shared upon request with proper permission.
- **Authors Contributions:** Each author has individually contributed to the article. Panchali Chakraborty conducted the experiments and wrote the manuscript. A.K. Barbhuiya supervised the research work and critically reviewed the manuscript.

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AUTHOR'S PROFILE

Panchali Chakraborty, Ph.D., a dedicated researcher in Water Resources Engineering. I have recently completed my Ph.D. from the Department of Civil Engineering at the National Institute of Technology Silchar, where I also received my M. Tech. in Water Resources Engineering. My research focuses on river erosion, seepage flow, open channel hydraulics, and scouring around hydraulic structures. I have conducted extensive laboratory and field investigations using advanced instruments such as Sontek ADV, Nortek Vectrino, and ADCP. I am passionate about research and teaching since they enable me to honestly share knowledge and explore creative approaches.

Prof. Abdul K. Barbhuiya, Ph.D., serves as a professor in the Civil engineering department at the National Institute of Technology Silchar, with extensive experience in water resources engineering. I did my B.E. (Hons) from REC Silchar, M.E. (first position) from Assam Engineering College, and Ph.D. from IIT Kharagpur. My research interests include sediment transport, hydraulic structures, fluvial hydraulics, and riverbank erosion. I have made contributions as a reviewer and subject expert in various national and international academic forums over the years. I am very dedicated to promoting research and education in my area while supporting academic excellence at the National Institute of Technology Silchar.