An experimental study on refugia condition for invertebrate (*Isonychia japonica*) by bluff bodies and its stability on the river bed

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ABSTRACT

Invertebrate behavior can be categorized into active walking, no walking and washout based on approach flow velocity. From this study, it can be concluded that invertebrates can actively walk for a depth averaged velocity less than 0.20m/s in a smooth bed condition (without roughness). Invertebrates showed no walking behavior at a depth averaged velocity more than 0.20m/s. Also, for a depth averaged velocity more than 0.40m/s, invertebrates were washed out. So, without roughness (WOR), the critical depth averaged velocity for no walking behavior is 0.20m/s and for washout behavior is 0.40m/s. It was also observed that invertebrates showed enduring behavior. The level of endurance was low during low flow conditions and high during high flow conditions.

Artificial roughness was used at the upstream to increase turbulence in the flume channel and to understand the effect of turbulence on invertebrate. With the roughness (WR), critical depth averaged velocity for no walking is increased from 0.2m/s (without roughness (WOR) case) to 0.3m/s but critical depth averaged velocity for washout is decreased from 0.4m/s (without roughness (WOR) case) to 0.33m/s. The depth averaged velocity cannot estimate well the invertebrate behavior.

So, local velocity at invertebrate height (4mm from bottom bed) was calculated by PIV. The results show that in a smooth bed (without roughness), local critical velocity is around 0.12m/s and 0.22m/s for no walking and washout respectively whereas in a rough bed (with roughness), local critical velocity is around 0.10m/s and 0.12m/s for no walking and washout respectively. The local critical velocity for no walking without roughness (0.12m/s) is similar to the value without roughness (0.1 m/s). For washout, the value without roughness (0.22 m/s) decreases when the roughness is introduced (0.12 m/s). So, the local velocity is found to be more important than depth averaged velocity for understanding invertebrate behaviors. Moreover, if depth averaged velocity is considered for invertebrate behavior analysis, then SC_S ,which is spatially averaged shear component of turbulent intensity is responsible for invertebrate's behavior of no walking and washout. However, if local velocity is considered, then with the introduction of roughness, at invertebrate height level, it can be concluded that local turbulent intensity, SC_L which is related to shear or drag force that act along their body is responsible for invertebrate's no walking behavior, whereas local turbulent intensity, VC_L which is responsible for lifting invertebrate is more responsible washout of invertebrates. So, this study shows that the

need for refugia is more under the turbulent condition of flow. Although this study doesn't accurately predict the drift distance after dislodgement due to flume size limitation but the study shows that dislodgement of invertebrate is not increased with flow and the shear stress required to dislodge an invertebrate such as I*sonychia japonica* on a immoveable bed is higher without roughness (3.41 N/m^2) than with roughness (0.12 N/m^2).

Different types of refugia were provided for invertebrates. Wooden blocks were used as refugia in the flume experiment. The two block setup with spacing (*B*) equal to height of the block (*H*) with small underscour and deep underscour at frontal block showed good results based on percentage invertebrate remain inside the flume. When refugia were provided, the invertebrates were able to walk for depth averaged velocity of 0.35 m/s that is 40% larger than that without refugia. With refugia, active walking and passive walking or no walking behavior was observed but washout behavior was not observed. With the introduction of refugia, the local velocity around the invertebrate height was reduced to less than 0.10m/s for high flow conditions. The upstream of block and gap inbetween blocks is more suitable in proving refugia than downstream of block for this type of setup.

Water flow pattern between two neighboring blocks (refugia), the pressure distribution around the scoured block (refugia), the optimal spacing between two neighboring blocks (refugia) when underscouring of first block (refugia) occurs were analyzed. The flow pattern investigated between two neighboring blocks (refugia) with underscour shows that flow pattern was different for different horizontal spacings and underscour depths. It was noted that an eddy was not generated with small horizontal gaps between two neighboring blocks (refugia) and that larger eddies were generated with wider gaps. Further, when underscouring was deep, eddies were generated but were small in size compared to eddies generated when the underscour was shallow.

The effect of wider horizontal gaps can be assumed to be significant in reducing the pressure on the bottom surface of a scouring block (refugia). For small and large underscours with a small horizontal space (*B/H*), the pressure distribution at the bottom surface decreases from front to back. However, for a deep underscour and a wide horizontal space ($B/H=1$), the pressure distribution was almost uniform at the bottom surface. Moreover, when the size of horizontal gaps was increased, the pressure acting on the top surface and front face was not altered much, while the pressure on the bottom surface was decreased and pressure on the rear face was increased.

The drag and lift characteristics also explain the importance of wider spacing between two neighboring blocks during underscouring of the frontal block (refugia). Under the same underscour conditions, the lift and drag coefficient decreased when the horizontal gap between two blocks (refugia) increased. Moreover, with the same horizontal gap between two blocks (refugia), the lift coefficient increased and drag coefficient decreased with increasing underscouring depth. The results demonstrate that wider horizontal spacing between two blocks (refugia) is effective to prevent or reduce the possibility of collapse of the front block (refugia) when the underscouring becomes deeper. In addition, with shallow underscouring depths, blocks (refugia) seemed to achieve stability when gaps between two blocks (refugia) (*B*) were equal to height of the block (refugia) (*H*).

Thus, the basic invertebrate behavior classification according to approach flow velocity is very important to understand the need for refugia during flood conditions and similar block arrangement (with horizontal spacing equal to height of the block) has a possibility to provide refugia in a stream. The flow pattern in-between two refugia and pressure distribution around scoured refugia has been clearly explained in this research. The blocks and its arrangement could be used as refugia during under scour conditions. The information in this research is useful for restoration projects in small stream for *Isonychia japonica* or similar *Ephemerella* species that have crawling behaviors and use small bed gravels to large rocks as refugia.

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A_D	frontal projected area (front area of block)
A_L	vertical projected area (top surface of block)
B	horizontal gap between block
C_D	drag coefficient
C_L	lift coefficient
CD_L	critical diagonal line that passes through block’s rotation center and block’s center of gravity
D_S	underscour depth
F_D	drag force
F_L	lift force
F_R	resultant force acting on the block
H	height of block
L	length of flume channel
L_b	length of block
L_I	distance of 90cm from upstream inlet
L_V	distance of 70cm from upstream inlet
t	time
u	velocity measured infront of scoured block and averaged from bed to block height
U	velocity at a given point
$\overline{U}$	mean velocity
U'	fluctuation or variation about mean
$\hat{U}$	turbulent intensity

U_a	depth averaged velocity
U_L	local velocity calculated at 4mm from bottom bed
$UC_{nowalking}$	critical depth averaged velocity for no walking
$UC_{washout}$	critical depth averaged velocity for washout
$UCL_{nowalking}$	local critical velocity for no walking
$UCL_{washout}$	local critical velocity for washout
W	width of flume channel
W_t	self weight of block
X_I	halfway length of the flume from inlet
$X1$	horizontal distance upstream of first block
$X2$	horizontal distance downstream of second block
Z	water depth
ρ	water density
γ	Size of angle made by resultant force F_R and CD_L
Θ	Angle made by resultant force on the block
Θ_1	Angle made by CDL on the block
SC_S	Spatial shear component of turbulent intensity
VC_S	Spatial vertical component of turbulent intensity
SC_L	Local shear component of turbulent intensity
VC_L	Vertical shear component of turbulent intensity

CHAPTER 1

INTRODUCTION

1.1. Research background

Benthic organisms (invertebrates) are an important food source for fishes, birds and mammals. In an invertebrate community inside a stream, different invertebrates have different habitat. Water flow (velocity) and related hydraulic phenomenon such as turbulence are major determinants of invertebrate's habitat and have critical impacts on aquatic communities (Statzner, Gore & Resh, 1988). Invertebrate habitat also depends on its ability to move in a stream. Based on the invertebrate's ability, they can be classified by creeping type (for e.g. *Ephemerella imanishii*, *Baetidae*, etc), swimming type (for e.g. *Baetiella japonica*, *Ephemerella setigera*, etc), attaching type (*Glossosoma sp.*, *Hydropsyche ulmeri*, etc) and case bearing type (*Micrasema hanasense*, *Goera japonica*, etc).

Ephemerella imanishii

(*Source: http://www.lberi.jp*)

Baetidae

(*Source*: *http://www.csuchico.edu /mmarchetti/FRI/Baetis/Baetis.html*)

Baetiella japonica

(*Source*: *http://d.hatena.ne.jp /OIKAWAMARU/20120313/P1*)

Ephemerella Setigera

(*Source*: *http://www.lberi.jp/ Root / jp/62pick/tayosei_db/ Imglist/ kagero.html.*)

Glossosoma

(*Source*: *http://www.pbase.com / tmurray74image/114344093*)

Hydropsyche ulmeri

(*Source*: *http://www.biopix.com/Hydrospyche*)
Biopix: N Sloth

Micrasema hanasense

(Source:*http://academic.smcvt.edu/Vermont_riverl*)

SAINT MICHAEL'S COLLEGE

Goera japonica

(*Source : COVERT PHOTO AGENCY*)

Fig.1.1. Different types of invertebrates based on their movement

Moreover, invertebrates can also be classified from adaptation in swift waters. Invertebrates that are found in quite waters rest at will, either by floating in the water or by standing on the bottom. But invertebrates living in swift streams are confronted with many conditions differing from those of quite water. The main problem in the swift stream is that invertebrates are in constant danger of being washed away and must maintain their position by adaptations which either enable them to withstand the current or to avoid it by crawling into crevices or under stones. So the adaptation of mayfly nymphs to swift water or running streams may be classified into three groups, namely: (1) those which enable them to swim vigorously through the water (2) those for withstanding swift current by holding to the bottom; and (3) those for avoiding the current by crawling into crevices or under stones (Dods and Hisaw, 1924). There is a need for more information on the species–specific movements and behavior of benthic invertebrates in response to changes in near-bed hydraulics (change in flow condition) (Lancaster, 1996). However, in a stream, invertebrates are exposed to several flow conditions, and its movement behavior will be influenced by the flow velocity. Lancaster (1999) discussed about the small scale movement of invertebrates with variations in flow. The active and passive movement of invertebrates was investigated and the increased discharge was found not to reduce the total number of individuals in experiment compared to control case. Hart and Finelli (1999) pointed out the importance of flow velocity that affects invertebrate assembly through diverse ecological factors such as habitat characteristics, resource acquisition, competition and predation. One of typical response of invertebrate to the flow is drift which determine dispersion and control invertebrate spatial distribution through various disturbance tolerance. Generally, drift of invertebrates consists of some types (Gibbins et al. 2010). One is *active drift* for finding new habitat and the second is *passive drift* by washed out from their habitat by current. Third is catastrophic drift which lost most of all invertebrate from the habitat with bed material movements. Catastrophic drift has been the subject of considerable interest because of the key role in structuring of benthic invertebrate communities (Lake 2000). This study focuses on the passive drift because of the implication of passive drift for tolerance limit against hydraulic force and turbulence as one of important disturbance factor.

Turbulence flow is another parameter that can alter the invertebrate behavior and its habitat in a stream. Turbulent flow is characteristic of upland rivers, including the habitats most commonly studied by ecologist, i.e. riffles and runs (Carling, 1992). Some of the advantage of turbulence to invertebrate is that it distributes fine organic particle evenly throughout the water column (McNair et al., 1997). Another advantages is that turbulent causes poor visibility, chaotic flow and buffering which hinder predators such as fish from attacking invertebrates , thus creating a refuge for invertebrates (Robson et.al., 1999). However, there is little study on the quantitative information of turbulence intensity on invertebrate behavior (Bouckaert and Davis, 1998: Robson et al., 1999). Moreover, the previous studies focused on the depth-averaged velocities rather than local velocities around invertebrate height (Brooker and Hemsworth, 1978: Ciborowski, 1983, Corkum et al., 1970). The effect of turbulence on invertebrate movement behavior needs to be clarified in relation to local velocity because in natural stream invertebrates are always exposed to the turbulent flow condition generated by large and small bed gravels.

High flow events in streams exert a strong influence on invertebrate fauna, typically causing substantial declines in abundance and diversity (Resh et., 1988; Lake, 2000). Therefore it is likely that invertebrates can avoid the destructive effects of high-discharge (flood) events to some extent by seeking and subsequently recolonizing from refugia (Sedell et al., 1990).The efficiency of flow refugia mechanism relies upon the movement behavior of invertebrates. Thus, it is very important to know how refugia can provide shelter to invertebrates during flood conditions. Cobb et al. (1992) have also explained the importance of refugia or microhabitat preference based on abundance near refugia. Although this information is useful for restoration projects, there exists no information on the hydraulic parameter such as invertebrate’s velocity preference around their body height near refugia. Moreover, the refugia for invertebrates need to be stable enough to provide shelter during floods.

1.2. Literature review

The research on refugia condition for invertebrates by bluff bodies on river bed and its stability has not been properly discussed till now. Before discussing about refugia, invertebrate behavior classification needs to be done in relation to approach flow velocity because some invertebrates may not need refugia at all.

Dods and Hisaw (1924) investigated on adaptation of mayfly nymphs on swift streams in relation to their body shape. They classified the species which can withstand the current and the species which avoid the current by living in crevices or under stones. He concluded that most of the mayfly nymph species that have flattened bodies avoid the flow and have capability to creep into narrow crevices under the stone. Moreover, only a few species, e.g., *Iron*, has flat body that doesn't avoid the current by living in crevices of various sorts, but live upon the expose surfaces of rocks, where they receive the full force of the strong current. However, his results are general and there is no hydraulic values mentioned in relation to condition at which mayfly nymphs avoid the current or the maximum velocity at which mayfly nymphs can withstand the flow.

Lancaster (1999) observed the small-scale movements and distribution patterns of invertebrates with variations in flow in an attempt to identify the various mechanisms by which organisms may use flow as refugia. Lancaster (1999) concluded that both active and passive modes of movement contributed to the accumulation of invertebrates near flow refugia. Some invertebrates actively crawled from high to low flow microhabitats (flow refugia). While others passively drifted to downstream side.

Not only flow conditions but the topography of bed materials, type of bed materials and the turbulence generated from it also affects the movement behavior of invertebrates. Previous studies such as Quinn et al. (1996) discussed about the effects of upstream bed roughness on invertebrates but their results mainly depended on the type of invertebrates used for the experiment. Their result shows that invertebrate abundance and diversity is decreased with the increasing upstream roughness but the effect was strongest for filter-feeders among three types (filter-feeders, collector-browsers and predatory invertebrates).

Robson et al. (1999) modified the flow conditions over patches of river bed in three rivers in south Western Australia to determine the effects of turbulence on benthic invertebrate communities. They concluded that there were no significant effects of increased relative turbulence intensity on any aspect of the invertebrate assemblage. But the invertebrate movement behavior for turbulence generated by roughness height equal to their body height is very important to understand the near bed interaction between invertebrates and flow. Although previous results are useful in understanding the invertebrate assemblage in relation to turbulence but the studies sometimes show contradictory results and lack important information such as critical velocity condition for invertebrate movement behavior.

During high flow or flood conditions, the basic need for refugia increases and invertebrates are forced to seek some kind of refuge. During floods, parts of stream bed that experience low hydraulic stress (especially the stream banks) act as flow refugia, such that invertebrates that happen to be in, or move into, these areas avoid entrainment. Flow refugia have been associated with single stable stones (Matthaei et al., 2000), microform bed clusters (Biggs et al., 1997), the hyporheos (Dole-Olivier et al., 1997), bar edges (Rempel et al., 1999), and woody debris (Palmer et al., 1996) , channel zones of relatively low velocity (Lancaster and Hilldrew,1993) and large boulders (Bouckaert and Davis, 1998). The importance of these refugia mentioned by different authors depends on the invertebrate’s movement type and life-stage.

Matthaei et al. (2000) investigated about the importance of stable stones for invertebrate refugia during the floods. They tested whether stable surface stones serve as invertebrate refugia in a New Zealand grave- bed stream. They concluded that stable surface stones were important invertebrate refugia during flood. Their conclusion was based on the presence of higher densities of invertebrates near refugia after flood. They also noticed that invertebrates may actively seek stable refugium stones, whereas many leave or are dislodged from unstable stones.

Small-scale cluster bed forms, or microforms, are prevalent features in rivers with gravel bed. Bedforms are produced by flow structure and movable sediment. Biggs et al. (1997) showed that clusters bedforms increases biological diversity by creating protection for invertebrates thus increasing the overall health of riparian ecosystems.

Dole-Olivier et al. (1997) used spates as a natural disturbance in a stream to study the resistance and resilience of invertebrates preferring interstitial (a minute opening or crevice between things) communities as habitat and his result suggest that hyporheic zones act as patchy refugium.

Rempel et al. (1997) suggests that invertebrates shifted from deep water to shallow water of the shore zone during annual flooding of a large grave-bed river. They showed the ecological importance of shore zone as flow refugium which was demonstrated by broad diversity of species with varying feeding behaviors and morphologies that concentrated in this zone during flooding.

Palmer et al. (1996) conducted a set of experiments to determine if invertebrate abundances are less affected in patches more sheltered due to the presence of woody debris dams. Their study show that removal of woody debris from the stream did not prevent invertebrates recovery throughout the channel; however, the presence of woody debris dams did confer greater resistance of invertebrates to floods (as measured by no decrease in abundance during flooding).

Lancaster and Hilldrew (1993) examined flow in nine streams in relation to refugia for invertebrates and found out that areas of bed maintaining low hydraulic stress throughout the discharge hydrograph could provide flow refugia for animals during spates. Although this information is useful for restoration projects, there exists no information on the hydraulic parameter such as invertebrate's velocity preference around their body height near refugia.

Bouckaert and Davis (1998) discussed about the influence of refugia such as a large roughness element (boulder), which predominate in determining microflows within its immediate surroundings, on invertebrate's assemblage. Their result suggests that the invertebrates were significantly richer and more abundant in the wake than at the front of boulders. Although these information about invertebrate assemblage and preference of wake region or upstream region is useful but there is no quantitative information about hydraulic parameters.

One of the main reasons for the collapse of refugia or obstructions is scouring of the bed around them. For example, woody debris positioned cross-stream directly affects the water flow and bed characteristics, including scour depth and the areas around it by changing the flow through the obstruction (Beebe, 2000). To clarify the reasons for the collapse of the blocks or obstructions, the drag and lift characteristics of the flow structures in the collapsed condition need to be understood. Previous studies on drag and lift forces acting on both river bed and bank protection focused on changes in the drag and lift coefficient due to 1) the block configuration (Tamura et al.,2003) and 2) the bed scour depth under the blocks (Fukuoka et al.,1988). The drag and lift forces are also changed by the obstruction shape, and the forces characteristics are utilized to reduce the fluid force.

For example, Rahman and Mashud (2010) discussed a method of reducing the drag and lift forces by transforming a sharp front nose of a blunt obstacle into a stepped nose obstacle. However, only a few studies have been conducted to elucidate the flow field in relation to refugia such as block scouring and block stability under scouring condition.

Shah et al. (2010) conducted experiments and numerical simulations to investigate the difference in flow patterns around a single obstacle (bed protection block) with and without underscouring and how it affects the drag and lift coefficients. The results of an earlier experiment using a single block with and without scouring showed that the lift coefficient is decreased when scouring under the block occurs.

Taylor et al. (2010) discussed the flow over square, circular, and triangular models on a flat plate. In that study, distinct circulation regions were created at the leading and trailing edges and in the wake region; however, the flow pattern for different spacings between two block models was not discussed. No study has reported the flow pattern between two rectangular blocks with different block spacing and scour conditions.

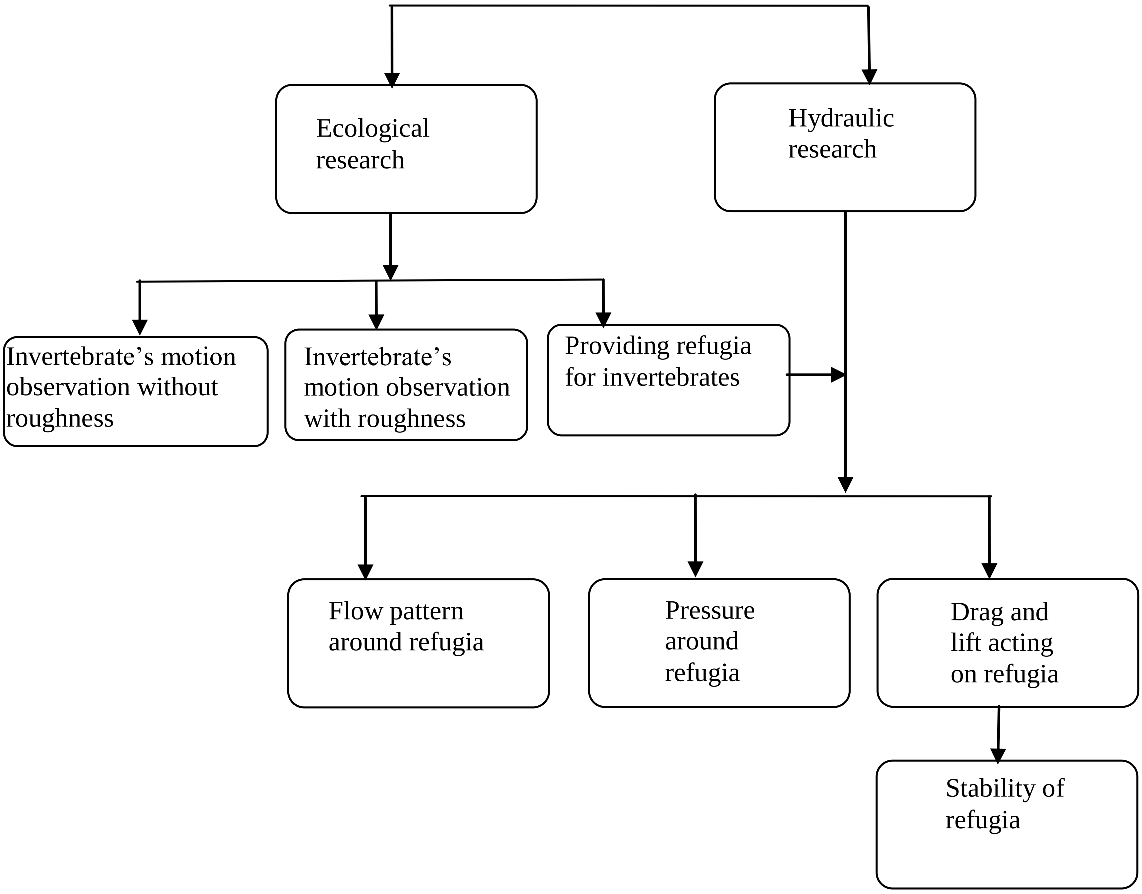
River protection blocks are usually chained together and placed on the bottom of the river bed with some space between them to protect the river bed from underscouring and to protect them from each other. An optimal distance between blocks for their stability under flood conditions may exist, but there is no information about it. In addition, the effects of different arrangements of blocks on scouring are still unclear.

Laskovski et al. (2007) measured the lift force of a solid material installed on a flat plate or on a slope, analyzed the collapse condition of bed protection blocks, and found that a lift force acts downward 83% of time, thus helping to keep the solid material at rest. Thus, there exists a finite probability of a positive lift force that is sufficient to permit the solid material to move. However, the stability of blocks in relation to drag and lift force in an underscouring condition has to be investigated.

1. 3. Purpose of this study

In this study, the movement behavior of invertebrates is investigated in relation to the change of approach flow velocity. Afterwards, the artificial roughness is set at upstream bed to analyze the effect of turbulence together with the change in approach velocity. Critical depth average velocity in relation to the invertebrate behavior was identified. Then suitable refugia were provided for the invertebrates during flood conditions. Then an optimal way of reducing the drag and lift force acting on the refugia was found for the stability of refugia. This study will provide basic information about invertebrate behavior in relation to change in flow velocity, need for invertebrate refugia and stability of refugia which could be applicable to natural streams for invertebrate management.

1.4. Research design



1. 5. Objective of this study

In this research, *Isonychia japonica* was chosen for the simple reason that they are one of the invertebrates that needs refugia during flood conditions because their natural habitat is near the stream rock bed. Furthermore, from the past research (Takemon, 1985). *Isonychia japonica* was found to be swimming and clinger type invertebrates, and the basic behavior could be further classified based on the flow condition (Takemon, 1985). This study hypothesizes that invertebrates show different behavior for various flow velocities, and that the movement behavior of invertebrates may also be affected by turbulence. Moreover, the blocks (bluff bodies) can be used as refugia for invertebrates. The information on block's arrangement and design could be helpful for invertebrate restoration projects.

Fig.1.2. Invertebrate (*Isonychia japonica)* used for this study
(*Source: NST Ecological Census and Modelling, http://blog.naver/nstdaily-SCH110618*)

So, the objectives of this study are (a) to categorize the invertebrate behavior based on approach flow velocity, (b) to define critical velocity for walking and washout or dislodgement under no refugia condition, (c) to assess the effect of turbulence generated by upstream artificial roughness on invertebrate behavior and compare the applicability between critical depth averaged velocity and critical local velocity for invertebrate movement behavior in relation to turbulence , (d) to provide suitable refugia for invertebrate and understand the importance of refugia in reducing the flow velocity near its habitat, and (e) to find a optimal way to reduce the drag and lift force acting on scoured refugia thus by making it stable and suitable habitat for invertebrates.

To achieve this objective, invertebrate's motion were observed and analyzed, the drag and lift characteristics of invertebrate’s refugia were investigated along with flow visualization using particle image velocimetry (PIV). Moreover, the pressure around the block model (refugia) was measured to understand the pressure distribution during under scoured conditions. In addition, the block stability in the underscoured condition was analyzed by using the obtained drag and lift coefficients.

CHAPTER 2

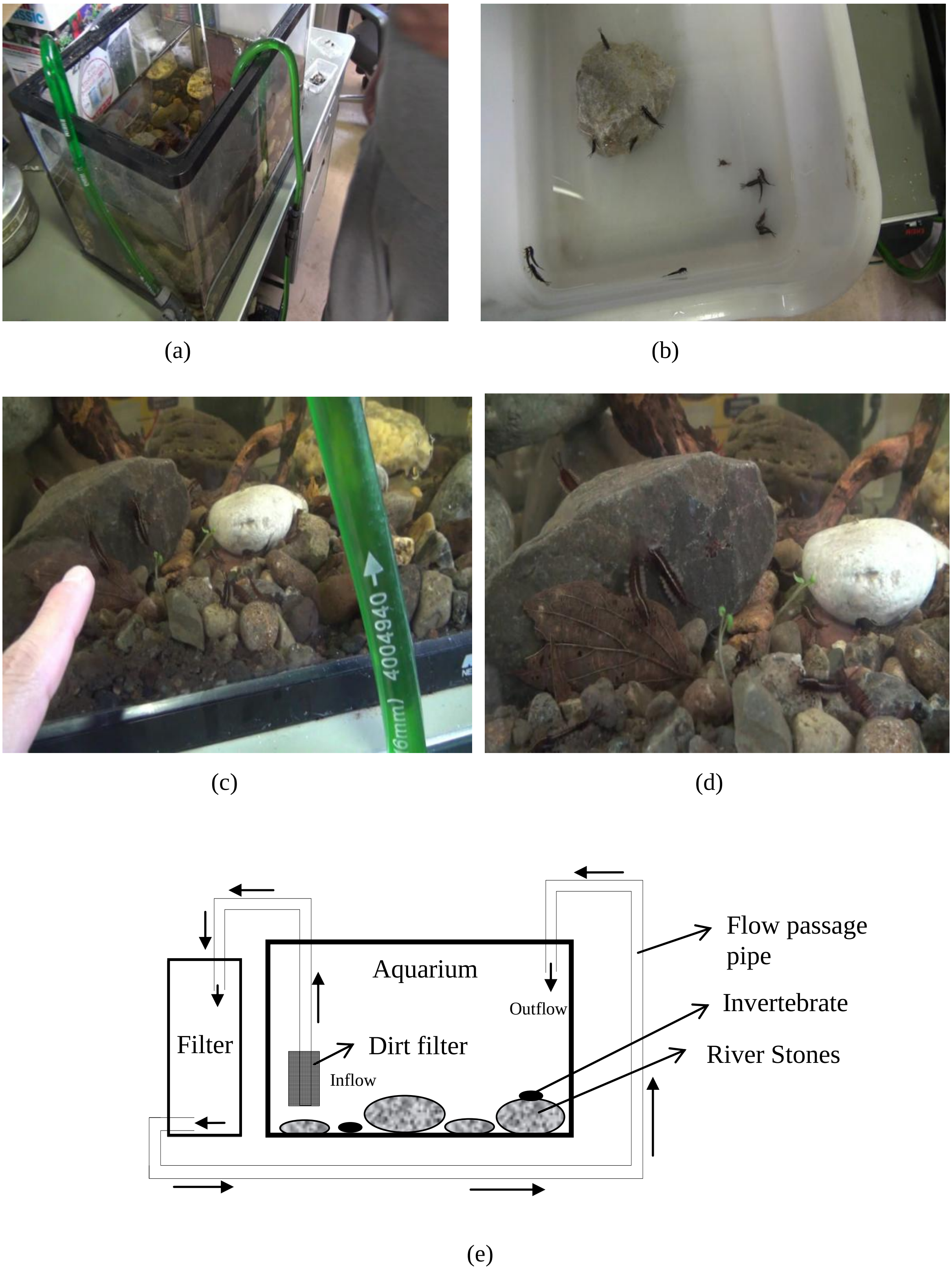
METHODOLOGY

In this chapter, the methodology and the experimental setup for invertebrate's motion observation and the methods to provide refugia are discussed. Moreover, the PIV procedure, pressure measurement methods, drag and lift force measurement techniques are also described in this section.

2.1. Invertebrate type and its perseveration inside aquarium

Invertebrate used in this experiment is *Isonychia japonica* species from family Emphemerella. They were collected from a stream in Fukushima Prefecture and were kept inside the aquarium during the experiment (Fig.2.1 (a)). Every week, a fresh batch of invertebrates was collected and was added inside the aquarium. The aquarium size of 30cm wide (*W*), 28cm deep (*D*) and 45cm long (*L*) was to keep the invertebrates. The body length (with tail) of the invertebrate is 20mm (average) with a standard deviation of 2.35 mm and the body height is 4mm (average). For every experiment, 16-21 insects were taken out of the aquarium and after the experiment, they were put back inside the aquarium. The tap water used in the flume channel and aquarium was dechlorinated. The weaker invertebrates were not used in the experiment. The water temperatures during the experiments ranged from 15 to 20 °C both in flume channel and aquarium.

Fig.2.1 (b) shows the bucket with the invertebrates inside. The bucket was used for transportation of invertebrates from aquarium to the flume channel safely. A stone was kept in the middle so that invertebrate would attach to it and be safe from movement of water during transportation. This method of transportation made easier to put invertebrates into the flume channel because they are attached to the stone and the whole stone could be lifted and placed inside the flume channel. Fig. 2.1 (c) shows the invertebrate inside the aquarium. They were mostly attaching at the surface of the rock. Some plant leaves were also put inside the aquarium which was used by the invertebrates as food. Fig. 2.1 (d) shows an invertebrate feeding on plant leave.



(a) (b)

(c) (d)

(e)

Fig.2.1. (a) aquarium (b) bucket for transportation of invertebrates (c) invertebrates inside aquarium (d) invertebrate feeding on leaves (e) schematic figure of aquarium setup

Fig.2.1 (e) shows the schematic figure of the aquarium setup with the flow mechanism. A filter was used at for the water purifications inside the aquarium. The flow was dropped from a height above the water depth (inside the aquarium) for the aeration. Some small fish were also put inside the aquarium to ensure the good quality of water. The assumption was such that invertebrate's heath will not be affected if the fish would be able to survive in that water. If the fish dies with the water quality inside the aquarium then invertebrate's health would degrade.

2.2. Invertebrate Behavior definition

To define the invertebrate behavior, first of all, the whole flume was divided into three regions (Fig. 2.2). Right wall region (RWR) is defined as the 6cm distance from the right wall. Likewise, left wall region (LWR) is defined as the 6cm distance from the left wall.

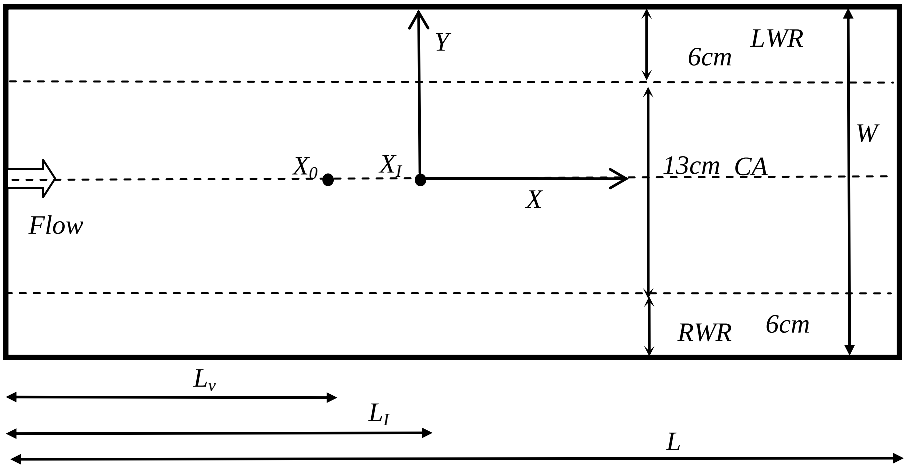


Fig.2.2. Definition of Left Wall Region (*LWR*), Central Area (*CA*) and Right Wall Region (*RWR*) in the flume (plan view): *L* is the length of the flume; *W* is the width of the flume; X_I is the initial position of invertebrate placement and the location of approach flow velocity measurement at a distance L_I = 90cm from upstream; X_0 is the location of approach flow velocity measurement at a distance L_V = 70cm from upstream.

From the preliminary investigation, the observed invertebrate behavior can be classified into four; 1) active walking, 2) no walking, 3) enduring behavior, and 4) washout.

2.2.1 Active Walking and no walking

“Active walking” is defined as the active movement of invertebrates in search for refugia (Fig. 2.3 and 2.4).This type of walking can be further classified into two types (Fig. 2. 3**)**. One is based on direction of invertebrate movement. They walk in left, right, up and down direction from its initial position (Fig. 2.3). Another type of active walking is based on the distance travelled by the invertebrates. They walk to reach the flume wall from central area (CA) (Fig. 2.2). This is long distance walking behavior. Also, they move to a short distance from its initial position (Fig.2.3). The number of invertebrates showing active walking behavior was calculated by counting the number of invertebrates moving from their initial position.

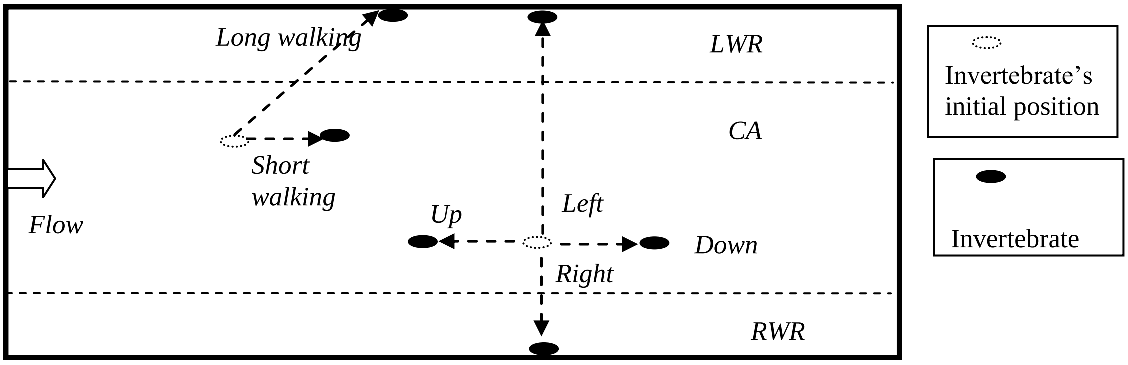
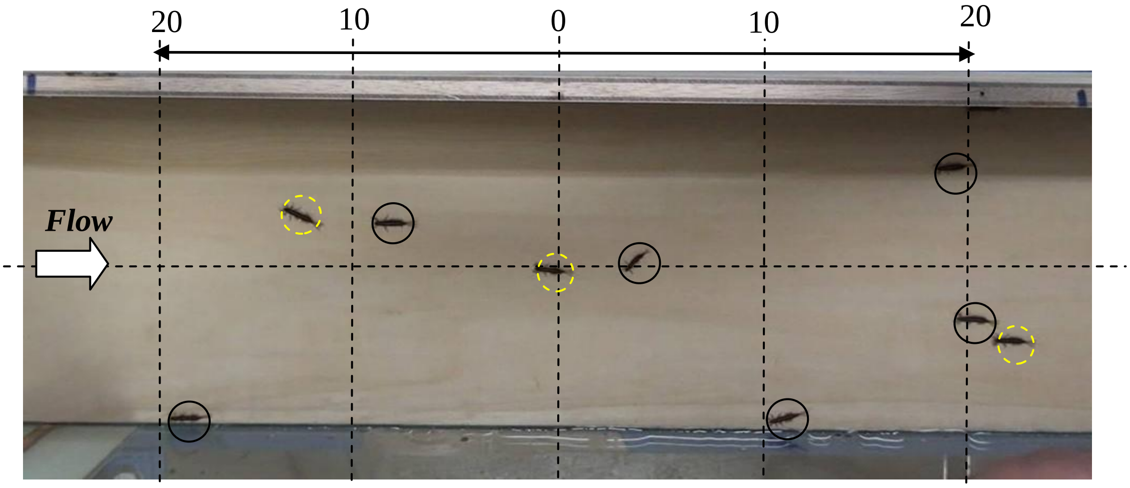
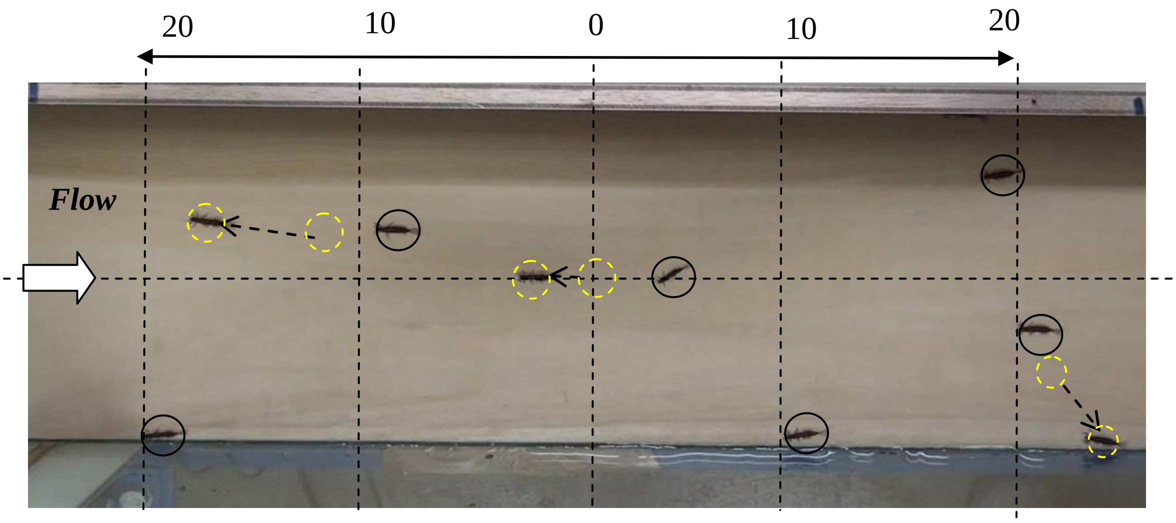


Fig.2.3. Schematic figure defining the active walking behavior of invertebrate; Left Wall Region (*LWR*), Central Area (*CA*) and Right Wall Region (*RWR*) in the flume (plan view)



(a)



(b)

Fig.2.4. Definition of “walking” and “no walking” behavior (a) initial position (b) position of invertebrates after 1 min. The dotted circles with arrow represent the walking invertebrates and not dotted circle represents no walking invertebrates. All the units are in cm (not to scale).

“No walking” is defined as the no movement of invertebrates upon change in flow condition (Fig.2.4). Invertebrates don’t change their position in this type of behavior. The black circles in the Fig. 2.4 (a) and 2.4(b) show no walking behavior.

2.2.2 Enduring behavior

(a)

(b)

Fig.2.5. Definition for enduring (a) enduring body posture during low flow condition (b) enduring body posture during high flow condition

"Enduring behavior" is defined as the adjustment of invertebrate body position and no movement of invertebrate upon the change in flow condition. Fig.2.5 (a) shows the invertebrate normal body position to flow when it can walk freely with small endurance. Fig.2.5 (b) shows the invertebrate body position when it cannot walk and the level of endurance is very high. It is difficult to differentiate no walking behavior from enduring behavior only from observation. In this experiment, physical disturbance (carefully touch invertebrates by a thin and long stick to check whether they move or not) was applied to check the behavior of invertebrate. However, careful consideration was taken not to disturb the flow pattern when touching the invertebrates by a stick.

2.2.3 Washout behavior

"Washout" is defined as the detachment or dislodgement of invertebrate from its original position by fluid force (Fig.2.6 and Fig. 2.7). Washout involves two type of mechanism. One is dislodgement of invertebrate from its initial position and reattachment of invertebrate at downstream of flume (Fig.2.6). Another one is dislodgement of invertebrate from its initial position and flushed out of the flume (Fig. 2.6)

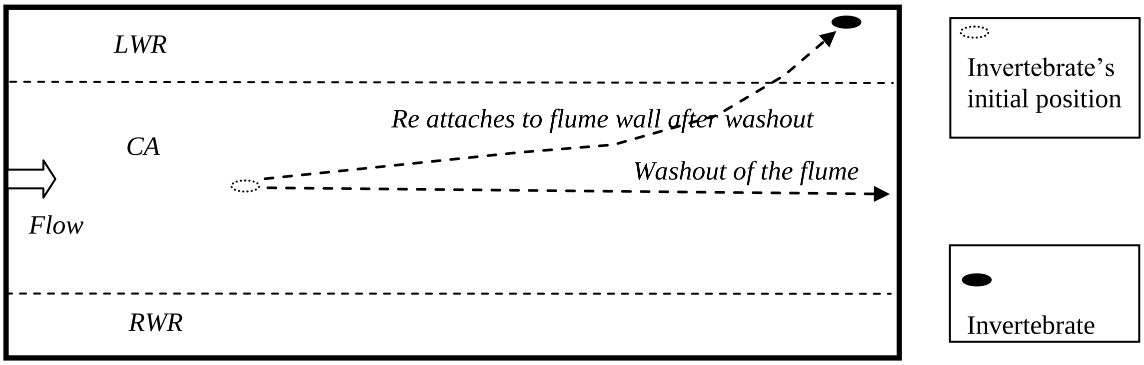
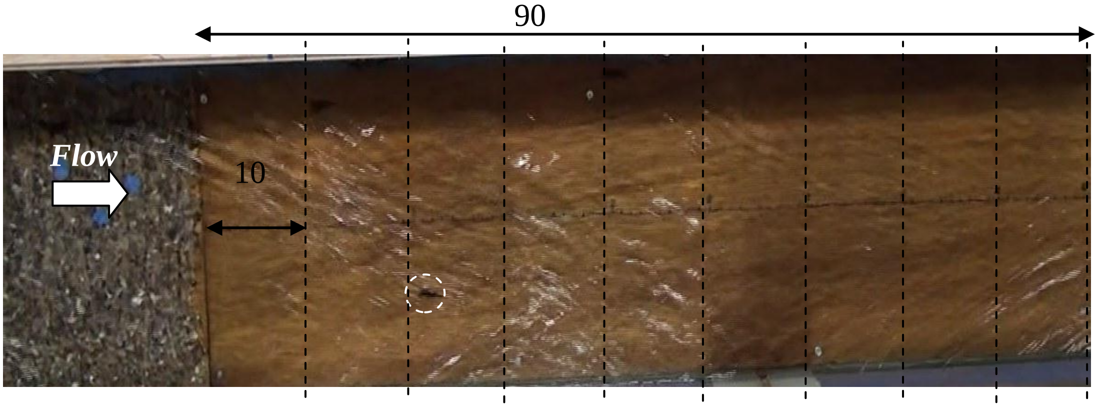
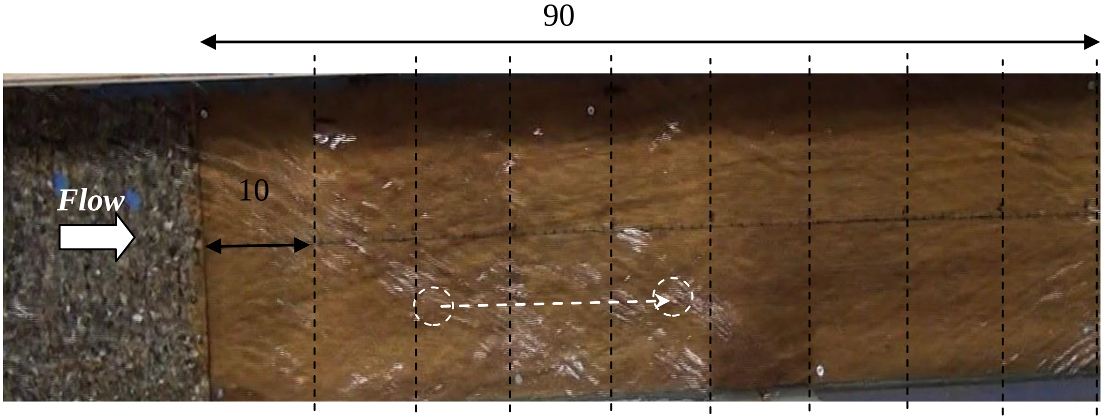


Fig.2.6. Schematic figure of washout behavior definition; Left Wall Region (*LWR*), Central Area (*CA*) and Right Wall Region (*RWR*) in the flume (plan view)

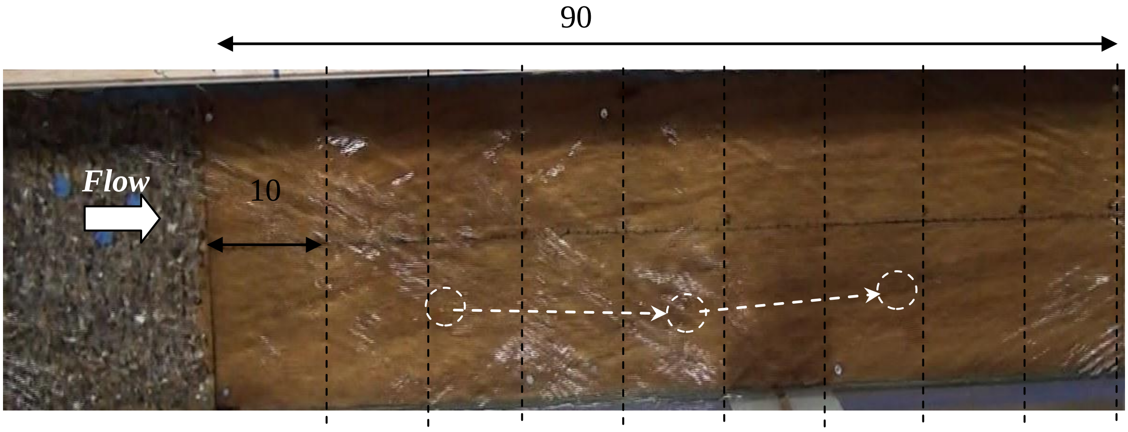
Fig.2.7 (a)-(d) also shows the washout behavior of invertebrate. Fig.2.7 (a) shows the start of washout and Fig.2.7 (d) shows the washout of invertebrate out of the flume channel in after 7secs.



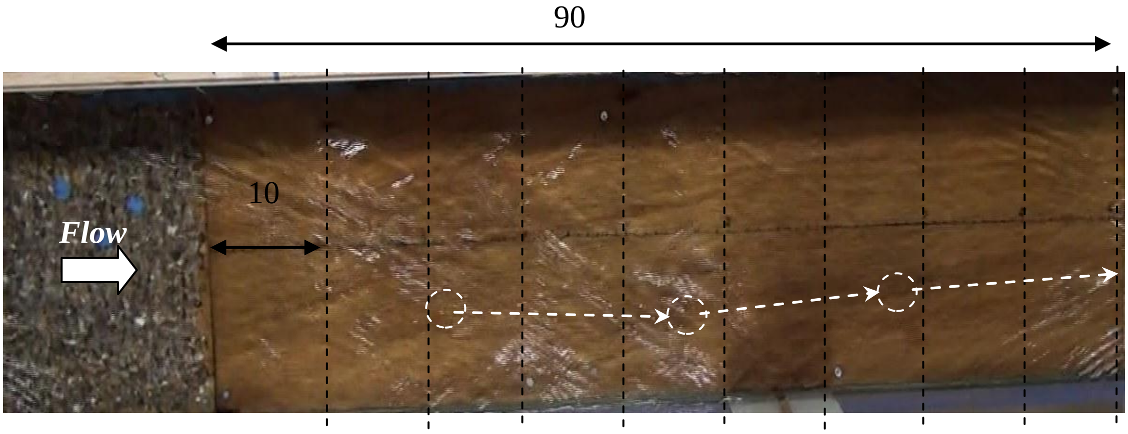
(a)



(b)



(c)



(d)

Fig.2.7. Definition for Washout behavior (a) initial position (b) after 3seconds of washout from its initial position (c) after 5seconds of washout from its initial position, (d) after 7seconds of washout i.e. washed out of the flume. The dotted circles represent the position during washout and arrow represents direction. All units are in cm (not to scale).

2.3. Flume setup, experimental cases and hydraulic conditions for investigating invertebrate behavior

The flume size of 25cm wide (*W*), 20cm deep (*D*) and 180cm long (*L*) was used for the experiment. The experiment was conducted for a range of flow velocities in Table 2-1, 2-2 & 2-3. Experiments were conducted for invertebrates without roughness (WOR), invertebrates with roughness (WR), invertebrates with single block as refugia (M1), invertebrates with two blocks as refugia (M2), invertebrates with two blocks as refugia with shallow underscour underneath the first block (M2-SS), invertebrates with two blocks as refugia with deep underscour underneath the first block (M2-DS). Wooden bed surface was used for the experiment with a Manning roughness coefficient (*n*) of 0.013. The experiment was also conducted with roughness. For roughness, gravel of 4mm height was used at upstream location for half of flume length. For refugia, wooden blocks of height (H =20mm) and length (L_b = 8cm) was used.

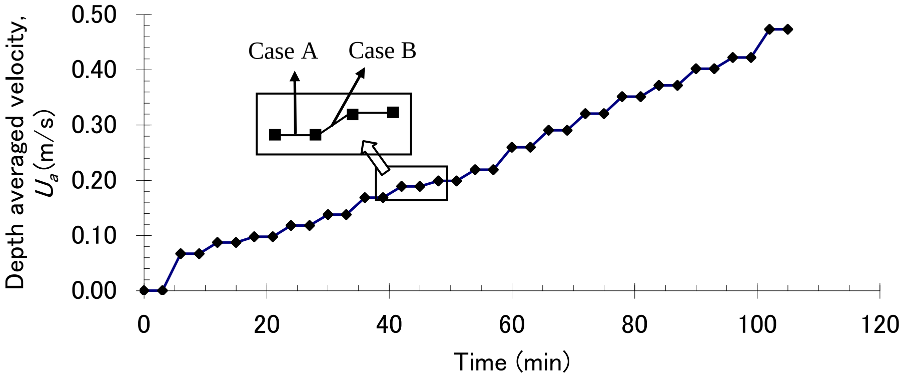


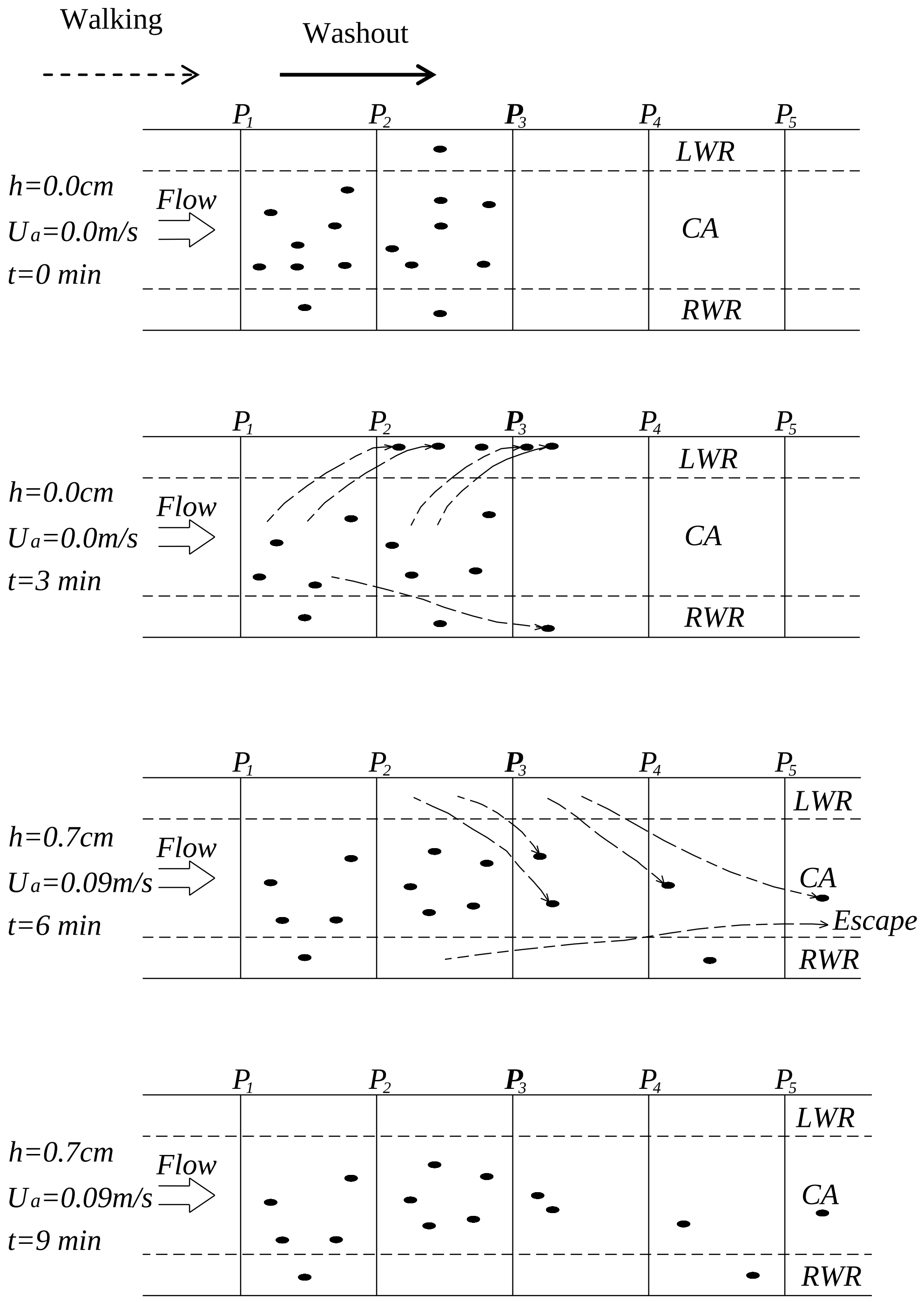
Fig.2.8. Velocity increment with time (without roughness-WOR); Case A represents uniform flow stage and Case B represents incremental flow stage

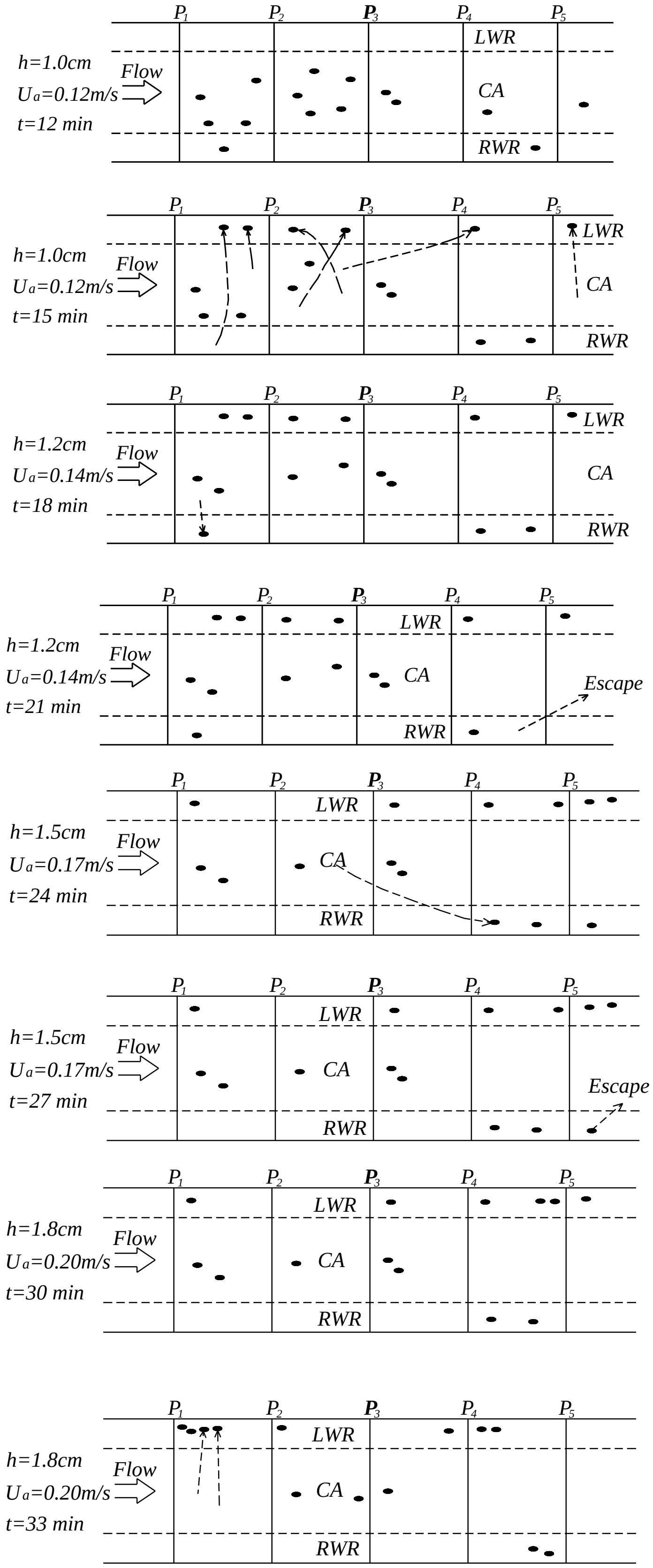
The experiments were conducted with three times. Fig.2.8 shows the velocity increment with time for the one of the observations with 18 hydraulic conditions (velocity change). The invertebrates were put in the flume, and the velocity was gradually increased. The velocity was increased gently for 3 minutes till the water inside the flume channel became uniform. When the velocity was uniform, the invertebrates were observed for 3 minutes (Case A), and their response to velocity increment was investigated. However, during velocity incremental stage also invertebrate's movements were observed (Case B).

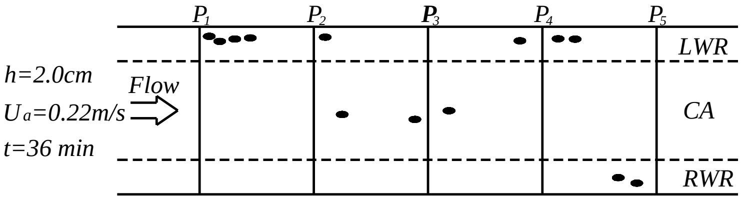
Similarly, for other cases such as with roughness (WR), invertebrates with single block as refugia (M1), invertebrates with two blocks as refugia (M2), invertebrates with two blocks as refugia with shallow underscour underneath the first block (M2-SS), invertebrates with two blocks as refugia with deep underscour underneath the first block (M2-DS), the velocity increment with time is shown in (Appendix 1).

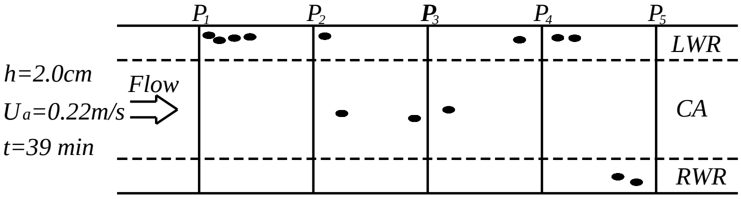
2.3.1. Invertebrate motion inside the flume channel for velocity increment with time (without roughness case –WOR)

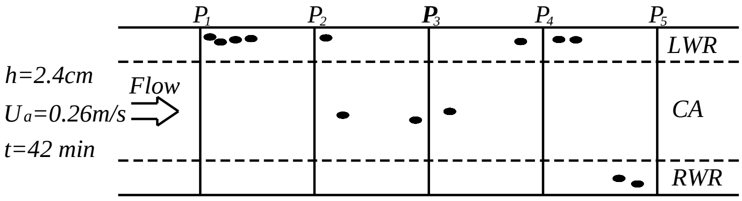
The figure 2.9shows the invertebrate position inside the flume channel during several hydraulic conditions (shown in Fig. 2.8). We can clearly see the walking behavior, no walking behavior, washout behaviors.

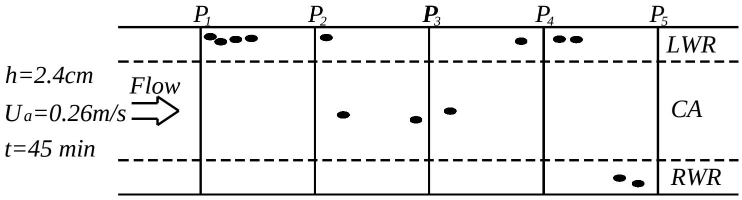


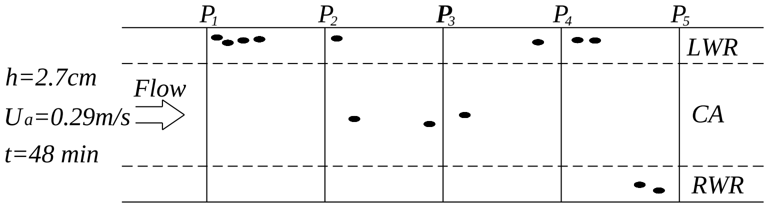

P1
P2
P3
P4
P5
LWR
CA
RWR
Flow
h=1.0cm
Ua=0.12m/s
t=12 min
h=1.0cm
Ua=0.12m/s
t=15 min
h=1.2cm
Ua=0.14m/s
t=18 min
h=1.2cm
Ua=0.14m/s
t=21 min
Escape
h=1.5cm
Ua=0.17m/s
t=24 min
h=1.5cm
Ua=0.17m/s
t=27 min
Escape
h=1.8cm
Ua=0.20m/s
t=30 min
h=1.8cm
Ua=0.20m/s
t=33 min

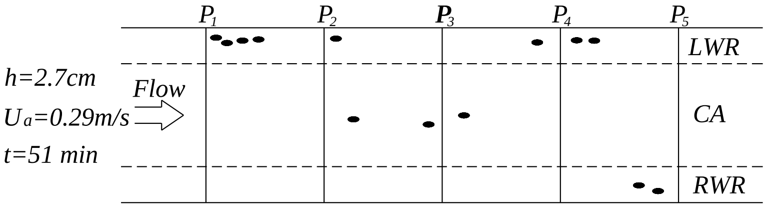

P_1
P_2
P_3
P_4
P_5
LWR
h=2.0cm
Flow
U_a=0.22m/s
CA
t=36 min
RWR

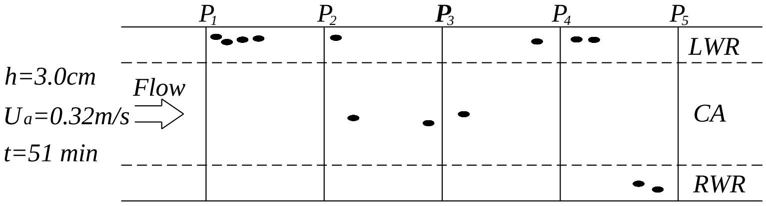

P_1
P_2
P_3
P_4
P_5
LWR
h=2.0cm
Flow
U_a=0.22m/s
CA
t=39 min
RWR

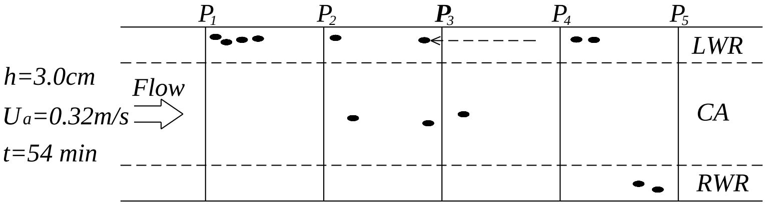

P_1
P_2
P_3
P_4
P_5
LWR
h=2.4cm
Flow
U_a=0.26m/s
CA
t=42 min
RWR


P_1
P_2
P_3
P_4
P_5
LWR
h=2.4cm
Flow
U_a=0.26m/s
CA
t=45 min
RWR


P_1
P_2
P_3
P_4
P_5
LWR
h=2.7cm
Flow
U_a=0.29m/s
CA
t=48 min
RWR


P_1
P_2
P_3
P_4
P_5
LWR
h=2.7cm
Flow
U_a=0.29m/s
CA
t=51 min
RWR


P_1
P_2
P_3
P_4
P_5
LWR
h=3.0cm
Flow
U_a=0.32m/s
CA
t=51 min
RWR


P_1
P_2
P_3
P_4
P_5
LWR
h=3.0cm
Flow
U_a=0.32m/s
CA
t=54 min
RWR

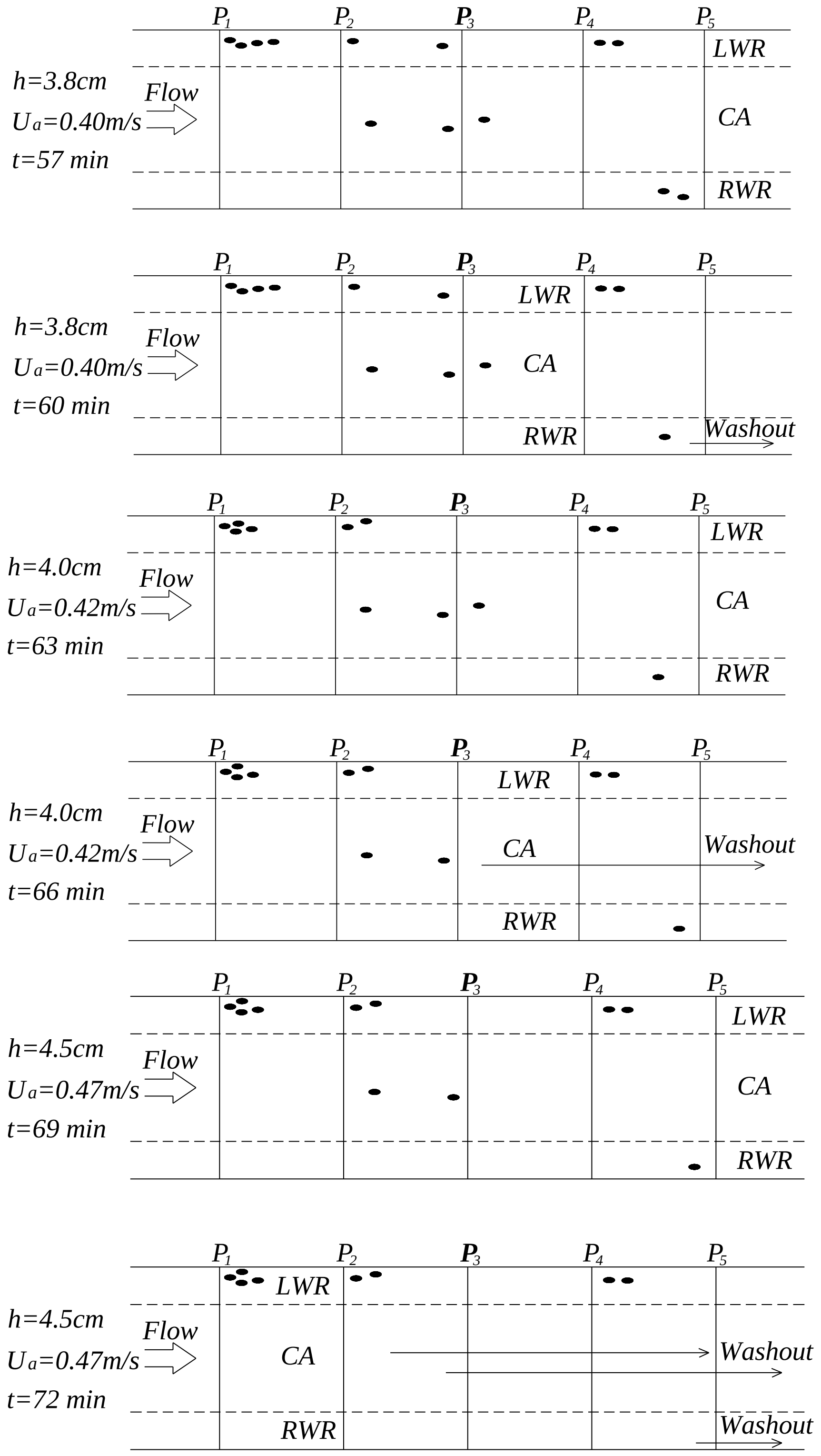
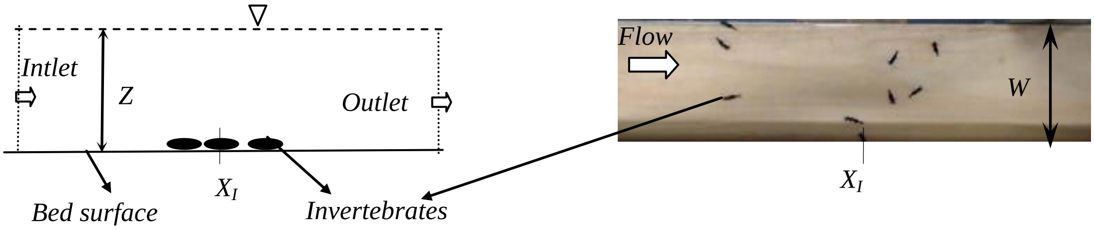


Fig.2.9. Invertebrate position inside the flume and their movement for velocity increment with time (without roughness case – (WOR)); See Fig. 2.8; *h* is the water depth, U_a is the depth averaged velocity, *t* is the time; black circle represents invertebrates; dotted line with arrow represents invertebrate movement; *LWR* is the left wall region, *RWR* is the right wall region, *CA* is the central area as defined in Fig.2.3.; P1 is the halfway length of the flume and the distance between P1 and P2 is 10cm. Similarly, P2, P3, P4, P5, P6, P7, P8, P9, P10 are 10cm far from each other.

2.3.2. Observation on invertebrates without gravel at upstream

Invertebrate movement was observed for flat bed without roughness (WOR) under different flow conditions. The schematic view and plan view of experimental setup is shown in Fig. 2.10 (a) and Fig. 2.10(b). Before the start of the flow, invertebrates were put at the center of flume channel at location X_I as shown in Fig.2.10. For each flow condition, velocity (U_a) was measured at upstream (location: X_I for) (refer Fig. 2.2) and averaged along the depth.



(a) (b)

Fig.2.10. Experimental setup without Roughness (WOR) (a) Schematic view of the flume with invertebrate without refugia (side view) (b) Flume with invertebrate without refugia (plan view); X_I is the halfway length of the flume.

Table 2-1 Hydraulic condition, number of invertebrate used, total flow conditions for the experiment

		Without roughness (WOR)
Water depth (m)		0 - 0.05
Velocity (m/s)		0 - 0.52
Number of the invertebrates used (individuals)		16-21
Hydraulic condition	1st observation (cases)	13
	2nd observation(cases)	18
	3rd Observation (cases)	18

The water depth (Z) ranged from 0-0.05 m and the depth average velocity ranged from 0-0.52m/s. One observation was conducted for three times. The number of invertebrates used for the each observation was from 16-21 individuals. After putting the invertebrates inside the flume channel, flow was started and the movements of invertebrates were noted. Those invertebrates that moved before the start of flow were neglected during the observation for different flow conditions.

2.3.3. Observation on invertebrates with gravels in upstream roughness

The same flume size of 25cm wide (*W*), 20cm deep (*D*) and 180cm long (*L*) was used for this experimental case. The experimental setup is shown in Fig. 2.11(a) and Fig. 2.11(b). The upstream half of the flume channel length was covered with the gravel of roughness height 4mm with a Manning roughness coefficient (*n*) of 0.029 to generate turbulence downstream from the roughness length. Experiment was conducted in an attempt to understand the invertebrate movement for the turbulence generated by roughness. The experiment was observed under different flow conditions which included different range of flow velocities shown in Table 2-2. The water depth (*Z*) ranged from 0-0.05 m and the depth average velocity ranged from 0-0.47m/s. the observation was conducted for three times. The number of invertebrates used for the each observation was from 16-18 numbers. For each flow condition, velocity was measured at upstream (location: X_0) (refer Fig. 2.2, Fig.2.10 (a) and Fig.2.10 (b)) and averaged along the depth. The invertebrates were also put at the location X_I which is the halfway length distance from upstream. After putting the invertebrates inside the flume channel, some went to the roughness area even before the start of the flow. Those invertebrates were neglected during the observation.

(a) (b)

Fig.2.11. Experimental setup with Roughness (WR) (a) Schematic view of the flume with invertebrate without refugia (side view) (b) invertebrate inside the flume (plan view)

Table 2-2 Hydraulic condition, number of invertebrate used, total flow cases for the experiment

		With roughness (WR)
Depth (m)		0 - 0.05
Velocity (m/s)		0 - 0.47
Number of the invertebrates used (individuals)		16-18
Hydraulic condition	1st observation (cases)	13
	2nd observation (cases)	13
	3rd observation (cases)	13

2.4. Velocity measurements

Two kinds of velocity were measured for the experiment. One is the depth-averaged velocity measured at half way length of the flume channel (P1) for invertebrate movement observation. Another is the detail measurement of velocity profile in longitudinal and vertical direction from middle to end of flume channel (P1-P9) in order to calculate turbulent intensity. The detail velocities were measured for roughness (WR) and without roughness (WOR) case.

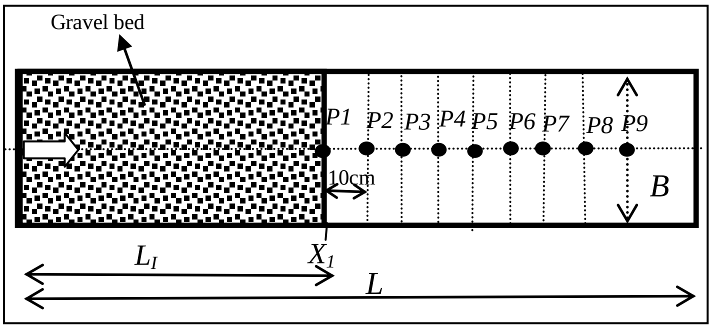


Fig.2.12. Flume arrangement of gravel bed with velocity measurement locations P1, P2, P3, P4, P5, P6, P7, P8, P9 and each measurement point at 10cm distance from each other .(Plan view)

For longitudinal velocity measurements, the velocity was measured using electro-magnetic flow meter (KENEK, MODEL: VM2000, KENEK CORPORATION, JAPAN) at every 10 cm from halfway length of flume as shown in Figure 1(f). The velocity measurement along depth has some limitations. The velocity could be measured only at a minimum height of 0.5-1.0 cm from bottom from the limitation of the instrument considering the accuracy. However, the data 0.5 cm from bottom bed surface was required because the invertebrate body height is roughly 0.4 cm. This electro-magnetic flow meter measurement was done mainly to measure detail velocity and then to calculate the turbulent intensity more than 0.5 cm from bottom. PIV (Particle Image Velocimetry) can also be used as another method to calculate turbulent intensities. For PIV, the video recording area should be painted dark to avoid reflection from wall and bottom surface and get clear image of the tracer. However, from the preliminary investigation, we confirmed that painted bed surface is not suitable for invertebrate behavior analysis because they couldn’t properly grasp to the flume bed surface under flow condition. Without painted bottom surface, the turbulence characteristics of a flow condition by PIV could be a little inaccurate at near bed region (smaller than 0.5 cm from bottom) because continuous data for calculating turbulence characteristics are sometimes difficult, although the average velocity can be obtained there by the PIV. Therefore electro-magnetic flow meter was used for the analysis of turbulent intensities using unpainted wooden bed surface. Vertical velocity profiles were measured at 0.5, 1, 1.5, 2 and 2.5 cm from the bottom bed. Flow was measured for 30s at each height using sampling rate of 100Hz (≈3000 measurements per sample). All the velocity measurements were done without using invertebrates.

Turbulence consists of random fluctuations in velocity and so it must be described by appropriate statistical methods (Tennekes and Lumley, 1972). The simplest approach is to partition quantities into mean values and fluctuations. For turbulent flow, velocities U and V in x (downstream) and y (vertical) direction, respectively, can be defined as follows:

$$U = \overline{U} + U^{'}$$

$$V = \overline{V} + V^{'} \qquad (1)$$

Where, $U\,and\ V =$ total instantaneous velocity at a given point in x and y direction, $\overline{U}\ \ and\ \overline{V} =$ mean velocity, and $U'\,and\,V' =$ fluctuation or variation about mean.

Turbulent intensity (the magnitude of the variation in velocity in the mean direction of flow) and relative turbulence intensity are accepted as being the most ecologically relevant descriptors of turbulence **(**Hart et al., 1996). As the invertebrates are directly affected by shear or drag force and lift force acting on them, this study use the turbulence related to shear force and lift force. The turbulent intensity related to shear component can be calculated as $\sqrt{\overline{|U'V'|}}$ (hereafter SC). Similarly, vertical component of turbulent intensity affecting lift can be calculated as $\sqrt{\overline{V^{'}V^{'}}}$ (hereafter VC). The turbulent intensity data obtained from this method is used to analyze the difference in SC and VC for invertebrate behavior during WOR and WR conditions of bed surface. In this study both spatial and local turbulent intensities were calculated. The spatial turbulent intensity related to vertical component (SC_S) and vertical component (VC_S) is calculated as

$$SC_S = \frac{1}{(M+N)}\sum_{i=1}^{M}\sum_{j=1}^{N}\left(\sqrt{\overline{|U'V'|}}\right)_{ij} \qquad (2)$$

$$VC_S = \frac{1}{(M+N)}\sum_{i=1}^{M}\sum_{j=1}^{N}\left(\sqrt{\overline{|V'V'|}}\right)_{ij} \qquad (3)$$

Where, M is the number of measurement points in longitudinal direction (i) and N is the measurement points in the vertical direction (j)

Also, the local turbulent intensity related to shear component (SC_L) and vertical component (VC_L) is calculated as calculated as

$$SC_L = \frac{1}{M}\sum_{i=1}^{M}\left(\sqrt{\left|\overline{U'V'}\right|}\right)_i \tag{4}$$

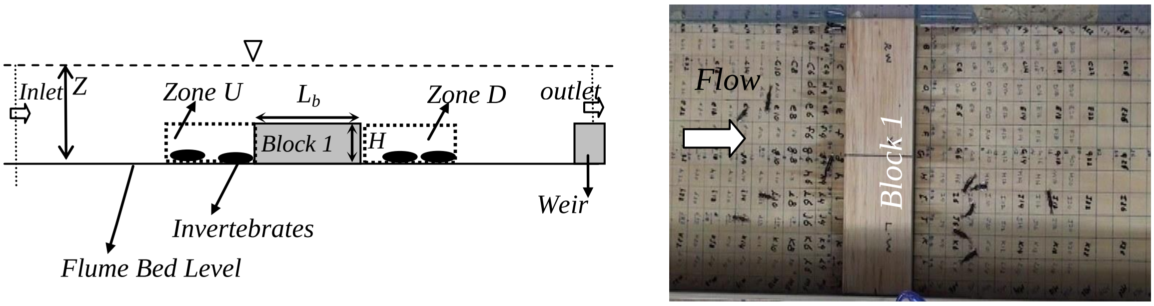
$$VC_L = \frac{1}{M}\sum_{i=1}^{M}\left(\sqrt{\left|\overline{V'V'}\right|}\right)_i \tag{5}$$

The local turbulent intensity is calculated at 0.5cm from the bottom bed surface and averaged along the flume length with M number of measurement points. Moreover, the turbulent intensity increment (TII) was calculated as

$$\text{TII} = ((\text{Value of WR}-\text{Value of WOR})/\ \text{Value of WR})\ \text{x}100 \tag{6}$$

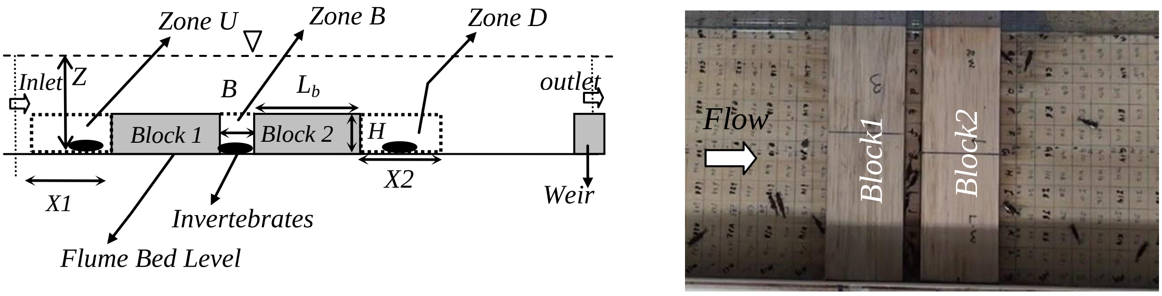
2.5. Providing refugia for invertebrates

For refugia, a good arrangement was required, which can simulate the natural habitat of invertebrates in a stream. For this purpose, several type of block arrangement wore provided for invertebrate refugia. Wooden block of height (H =20mm) and length (L_b = 8cm) were put inside the flume for this study. Fig.2.13 (a) shows the side view of single block (M1) arrangement and Fig. 2.13(b) show plan view of the single block (M1) arrangement where invertebrates were put at upstream (Zone *U*) and downstream of block (Zone *D*). Fig.2.14 (a) shows side view of the two blocks (M2) arrangement and Fig.2.14 (b) shows the plan view of the two block (M2) arrangement. A small gap (B) of 20mm (equal to body length of invertebrates) was placed between two blocks for Case M2. At downstream of Block2, a small weir was constructed at the exit of the flume to create a pool. Zone *D* is defined as the upstream region of Block1 with distance *X1*, Zone *B* is defined as the region between Block1 and Block2 with horizontal distance *B*, and Zone *D* is defined the region downstream of Block2 with horizontal distance *X2* (Fig. 2.14). Invertebrates were put at upstream of Block 1 (Zone *U*), in-between Block 1 and Block 2 (Zone *B*), and downstream of Block 2 (Zone *D*).



(a) (b)

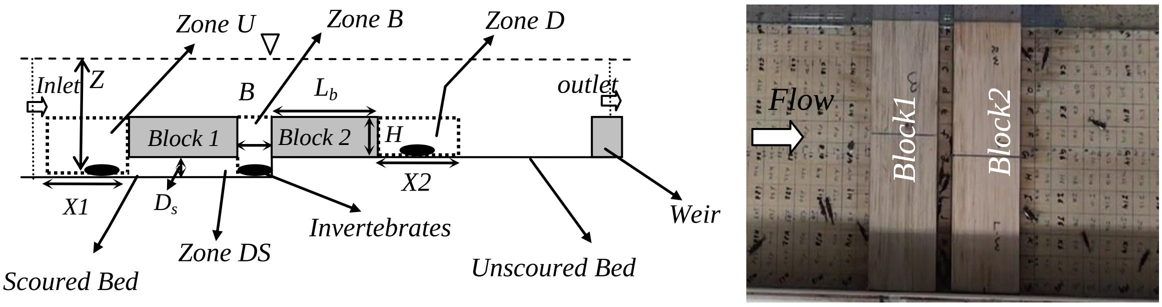
Fig.2.13. Arrangement of single blocks for refugia (M1), location of invertebrates (a) side view (b) plan view



(a) (b)

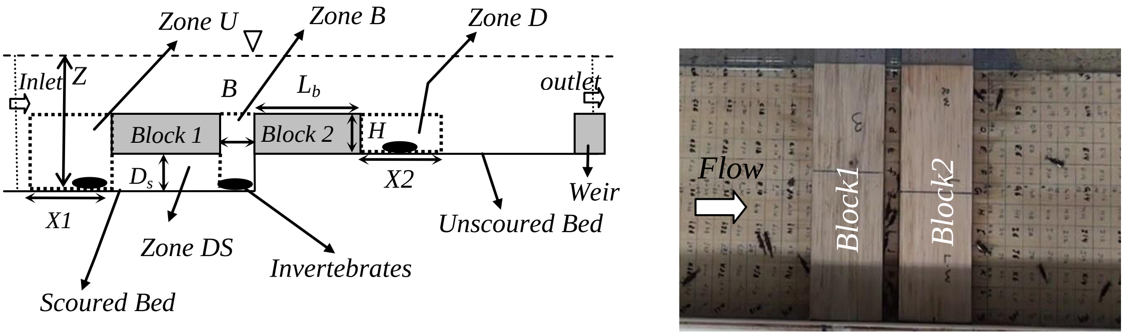
Fig.2.14. Arrangement of two blocks for refugia without underscour (M2) of bed, location of invertebrates, and the definition of different characteristic zone (a) side view (b) plan view

Fig.2.15(a) and Fig.2.15(b) shows side view and plan view of the two block arrangement with shallow underscour depth (D_s/H of 0.05, where, D_s is the underscour depth, H is the height of the block as refugia) beneath the Block 1 (Case M2-SS). The invertebrates were put at upstream of Block 1 (Zone *U*), in-between Block 1 and Block 2 (Zone *B*), and downstream of Block 2 (Zone *D*).The underscour depth below Block 1 was 1mm. The simple setup of shallow scouring depth (1mm) less than invertebrate body height (4mm) also removed possibility that individuals could take refuge underneath block .Fig. 2.16(a) and Fig. 2.16(b) show the side view and plan view of the two block arrangement with deep underscour depth (D_s/H of 0.25, where, D_s is the underscour depth, H is the height of the block as refugia) beneath the Block 1 (Case M2-DS). The invertebrates were put at upstream of Block 1 (Zone *U*), in-between Block 1 and Block 2 (Zone *B*), and downstream of Block 2 (Zone *D*). In this case there was the possibility that the invertebrate could take refugia at the underscour area beneath the Block1 because the underscour depth, D_s, for this case was 5mm which is greater than invertebrate height (4mm)



(a) (b)

Fig.2.15. Arrangement of two blocks for refugia with small underscour (M2-SS), initial location of invertebrates, and the definition of different characteristic zone (a) side view (b) plan view



(a) (b)

Fig.2.16. Arrangement of two blocks for refugia with deep underscour (M2-DS), initial location of invertebrates, and the definition of different characteristic zone (a) side view (b) plan view

Table 2-3 Hydraulic condition, number of invertebrate used, total flow conditions for the refugia; Case M1, Case M2

		Refugia				
Cases		Case M1		Case M2		
Depth (m)		0 - 0.087		0 - 0.097		
Velocity (m/s)		0 - 0.42		0 - 0.41		
Number of the invertebrates used (individuals)		Zone U	Zone D	Zone U	Zone B	Zone D
		7	7	7	7	7
Hydraulic condition	1st observation (cases)	19		19		
	2nd observation (cases)	15		-		

The invertebrate movement was observed under different flow conditions which included different range of flow velocities as shown in Table 2-3**.** The water depth (*Z*) ranged from 0-0.087m and the depth average velocity ranged from 0-0.50m/s for single block case (M1). The observation was conducted for 2 times which had 19 and 15 hydraulic conditions. The number of invertebrates used for the each observation was 7 (individuals) at upstream zone (Zone *U*), and 7 (individuals) at downstream zone (Zone *D*) for Case M1. Similarly, for two block case (M2)**,** the water depth (*Z*) ranged from 0-0.097m and the depth average velocity ranged from 0-0.50m/s. The number of invertebrates used for each time was 7 (individuals) at upstream zone (Zone *U*), 7 (individuals) inside gap (Zone *B*) and 7 (individuals) at downstream zone (Zone *D*) for Case M2.

Table 2-4 Hydraulic condition, number of invertebrate used, total flow conditions for the refugia; Case M2-SS, Case M2-DS

		Refugia		
Cases		Case M2-SS		Case M2-DS
Depth (m)		0 - 0.10		0 - 0.10
Velocity (m/s)		0 - 0.50		0 - 0.50
Number of the invertebrates used (individuals)		Zone U	Zone B	Zone D
		7	7	7
Hydraulic condition	1st observation (cases)	10		12
	2nd observation (cases)	12		19
	3rd observation (cases)	12		10

Similarly, the hydraulic condition for Case M2-SS and Case M2-DS is shown in Table 2-4. The water depth (*Z*) ranged from 0-0.10m and the depth average velocity ranged from 0-0.50m/s for two blocks with shallow underscour (M2-SS) and two blocks with deep underscour (M2-DS).The observation was conducted for 3 times. The number of invertebrates used for each observation was from 7 (individuals) at upstream zone (Zone *U*) and 7 (individuals) at downstream zone (Zone *D*). Moreover, the observation was conducted for 10, 12, and 12 hydraulic conditions (change in velocity condition). Similarly, for two blocks with deep underscour (M2-DS), the observation was conducted for three times with 12, 19, and 10 hydraulic conditions (change in velocity condition) respectively. For each flow condition, velocity (U_a) was measured at upstream (location: X_0) (refer Fig.2.2) and averaged along the depth.

2.6. Particle image velocimetry (PIV)

2.6.1. PIV without blocks as refugia

A PIV method was used for obtaining local average velocity near the bed (o.4 cm from bottom) that cannot be obtained by electromagnetic flow meter. A PIV setup in a flume without any refugia is shown in Fig.2.17.Aluminum particles were used as tracers for visualizing flow. The green laser (Green Laser Sheet of 200 m/G, Katoh Koken Co., Ltd.) was mounted at the top of the flume. A high-speed digital camera (K-II, Katoh Koken TV Zoom lens H851V, Katoh Koken Co., Ltd.) was placed near the flume wall. For Case WOR and Case WR, the video was taken from halfway length (P1) to the 40cm (P5) distance from halfway length of the flume channel and the center of the channel (refer Fig.2.12 for definition of P1 & P5). The recorded flow video analysis was conducted at P1, P2, P3, P4, and P5 which are 10cm distance apart. The video recording was done in two parts due to limitation of camera lens. First part includes the video coverage range from P1 to P3 and the second part includes the video coverage range from P3 to P5. The objective for the flow visualization was to understand the velocity profile and the near bed velocities affecting the invertebrate behavior during low and high flows. The video was recorded at 100 frames per second and saved at 30 frames per second. The recording length was at least 1 minute. The captured image recordings were analyzed by commercial software named flow expert (Version 1.0.8.0 build) developed by KATO KOKEN.

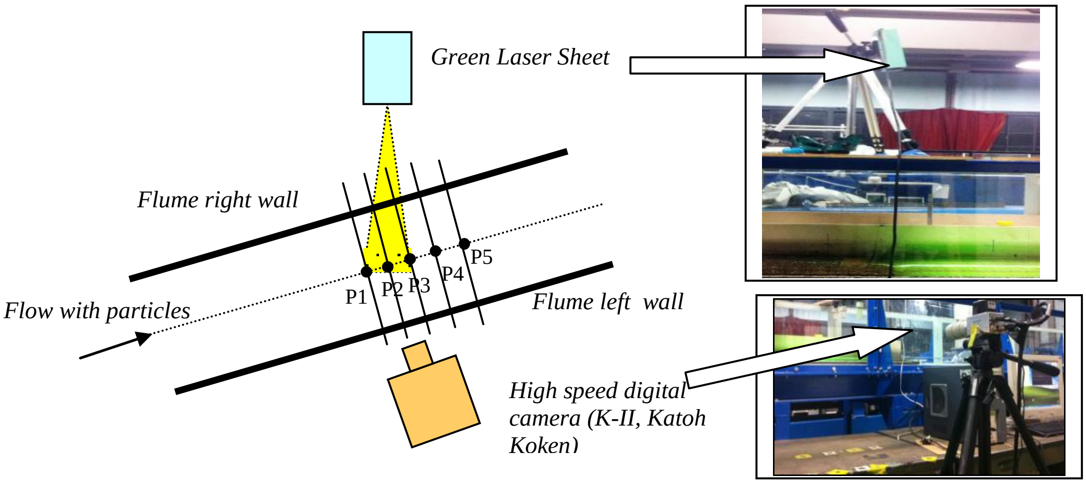


Fig.2.17. PIV setup in a flume channel without any refugia (horizontal view)

2.6.2. PIV with blocks as refugia

A PIV setup in a flume with blocks as refugia is shown in Fig.2.18. A mixture of aluminum particles and KC Flock (Nippon Paper Chemicals Co., Ltd., finely sieved powdered cellulose made from wood pulp) were used as tracers for visualizing flow. The mean diameter of the particles (tracers) was approximately 10 µm. A high intensity and high frequency (200 Hz) laser (Green Laser Sheet of 200 m/G, Katoh Koken Co., Ltd.) was used to illuminate the tracers. A high speed digital camera (K-II, Katoh Koken TV Zoom lens H851V, Katoh Koken Co., Ltd.) with a specification of 8.5–51 mm f/1.6 was used to record images.

The green laser was mounted at the top of the flume. A high-speed digital camera was placed near the flume wall. The video was taken inside the gap zone (Zone *B*), upstream of first block (Zone *U*) and downstream of block 2 (Zone *D*) halfway from flume wall. The optimal concentration of tracer particles was determined for high video quality with a clear flow pattern before the start of actual experiment. The video was recorded at 100 frames per second and saved at 30 frames per second. The recording length was at least 1 minute. The captured image recordings were analyzed by commercial software named Dipp Flow V.1.21kp (Ditect Co. Ltd.).

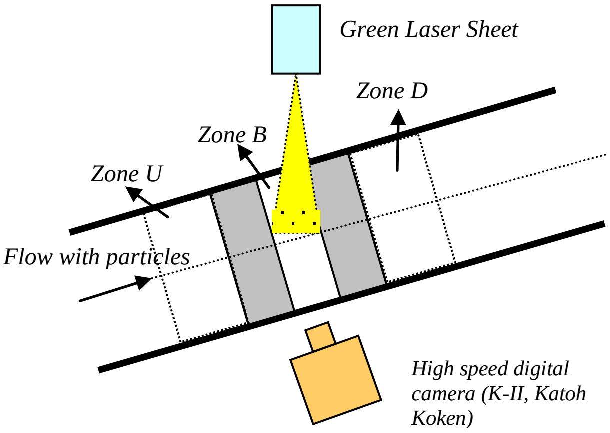


Fig.2.18. PIV setup in a flume channel with block as refugia (horizontal view)

2.7. Pressure, drag and lift force measurement for scoured block (refugia)

For practical purposes, Tamura et al.(2003) conducted experiments to clarify drag and lift characteristics of bed protection blocks using 85 block shapes and a wide range of Reynolds numbers ($Re = uH/v$, where u is an average approach velocity, H is height of a block, and is v the kinematic viscosity of water). The relationship between drag coefficients, lift coefficients, and Reynolds number was investigated and revealed that if the shape of the blocks is the same, then drag and lift coefficients values are not much changed at Reynolds numbers of 1,000 or greater. However, the drag and lift coefficients varied with the change in the shape of the bed protection blocks. Later, Inoue et al. (2009) conducted experiments using three different block heights with the same stream and cross-stream length, 8 and 50 cm, respectively. The heights of the bed protection block models used in that experiment were 1.9 cm, 2.8 cm, and 3.8 cm. The drag and lift coefficients changed with the height, and the 1.9 cm high block expressed well the range of the coefficients investigated by Tamura et al. (2003). In this study, although the Reynolds number was different from that of Inoue et al. (2009) (Reynolds number =14,000 based on block height), the 2 cm block height was chosen considering the similarity of drag and lift coefficients of the actual block.

Fukuoka et al. (1988) reported that the lift force reaches its maximum when the critical non-dimensional underscour depth D_s/H (D_s: underscour depth, H: block height) is 0.2 to 0.3. Based on that, block models were placed across the flow and the non-dimensional underscour depth D_s/H of the first block was changed from 0.05 to 0.25 with a non-dimensional horizontal spacing B/H (B: gap between two adjacent blocks) of 0.25, 0.5, 0.75, or 1 between the first and second blocks. For each underscour depth (D_s/H), there were four different horizontal spacings (B/H). Thus, in total, 20 experiments were conducted.

Laboratory experiments were conducted in a water flume that is 15 m long and 0.5 m wide. The experiment was carried out with a fixed 1/700 bed slope, 8 cm water depth, and 0.35 m/s approach flow velocity. The Reynolds number based on the height of the block and mean velocity of approach flow was set at 7,000. The experimental flow condition was subcritical with a Froude number of 0.40. The ratio of water depth to block height was four in all cases.

Zone *B* is defined as the horizontal gaps between the first and second block. Zone *DS* is the scoured zone beneath the first block. *Z* is the water depth. Two types of block arrangements were used depending on the experimental objective. One was to measure PIV and pressure. For PIV and pressure measurement, the first block was attached to the side walls of the flume in order to keep it in a fixed position against the flow. The other experiment was the direct measurement of drag and lift forces on the first block. In this experiment, the first block was not attached to the side wall of the flume. A small gap was kept between the block side surface and flume side walls. The second block was attached to the bed and side wall of the flume at all times for all experiments.

2.7.1. Pressure measurement

Micropressure transducers (P303V, SSK Co., Ltd.) with a measuring capacity of 0.2 kg/cm^2 at 5.6 kHz were placed around the surfaces of the model block at mid span. Figs. 2.19 (a), (b), (c) & (d) shows block arrange for pressure measurement and pressure tap locations. Pressure was measured at three points each on the top and bottom surfaces of the block. They are labeled as the first point (FP), middle point (MP) and last point (LP). The pressures were also measured at two points each on the front and rear faces. They are labeled as the top point (TP) and bottom point (BP). The pressure data was recorded for 30sec at 100 Hz.

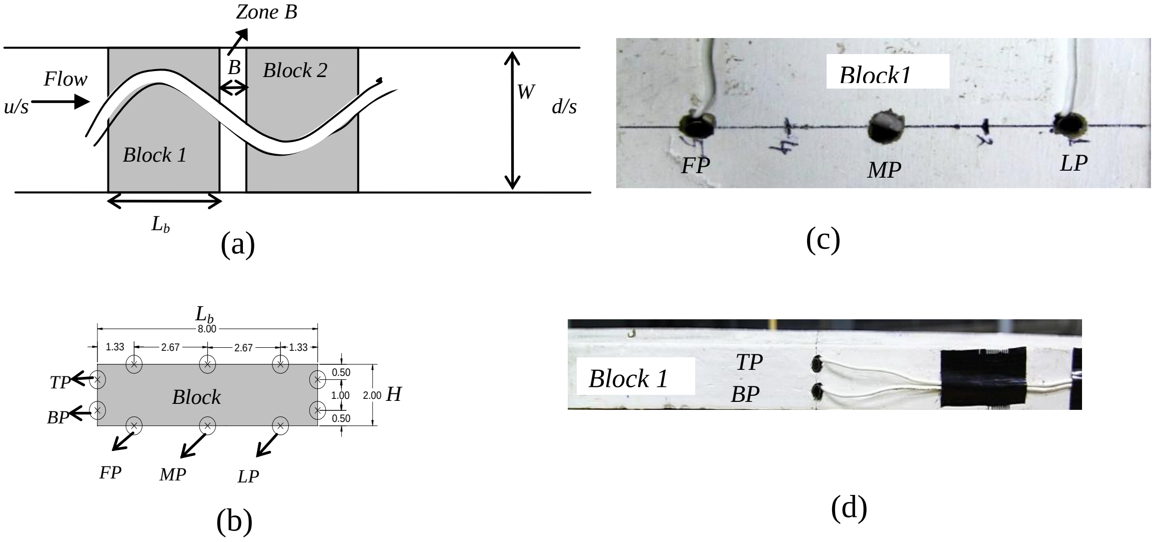


Fig.2.19. (a) Schematic block arrangement in plan view (b) block (refugia) with pressure tap points; *X* indicates pressure taps, and circles are areas covered by the instrument. Units of distance are in cm. *FP*=first point, *MP*=middle point, *LP*=last point, *TP*=top point, *BP*=bottom point. (c) Pressure points *FP*, *MP*, & *LP* (d) Pressure points *TP* and *BP*

The surface pressures were integrated at front, back, top, and bottom sides of the model to obtain the drag and lift forces. The drag and lift forces from the pressure measurements were compared with the drag and lift forces from the direct measurements to check their accuracy.

2.7.2. Drag and lift force measurements

A two-axis load cell (streamwise (X) and vertical (Z) directions, type LB-60, SSK Co., Ltd.) that has a resolution of 1/1000 and can measure 10N was used to measure the drag and lift forces on the block model. A photograph of the model locations and measurement technique is shown in Fig.2.20. The lift force (F_L) and drag force (F_D) of the first block were measured directly by the two-axis load cell referring the technique in previous similar experiments (Takemura and Tanaka (2007); Tanaka and Yagisawa (2010)). Lift coefficient (C_L) and drag coefficient (C_D) are defined as:

$$F_L = 0.5\, C_L \rho u^2 A_L \tag{7}$$

$$F_D = 0.5\, C_D \rho u^2 A_D \tag{8}$$

where ρ is the water density (kg/m^3), u is the velocity in front of the block, averaged from the bed to the block height level (m/s), A_L is the vertical projected area (top surface area) of the block (m^2), and A_D is the frontal projected area of the block (m^2).

One major problem with lift force measurements of long wooden models (such as those used in this experiment) is that the experimental results sometimes show negative lift force. It was observed that a slight tilt toward one of the sides produces such experimental results. This problem was solved by making the model absolutely horizontal.

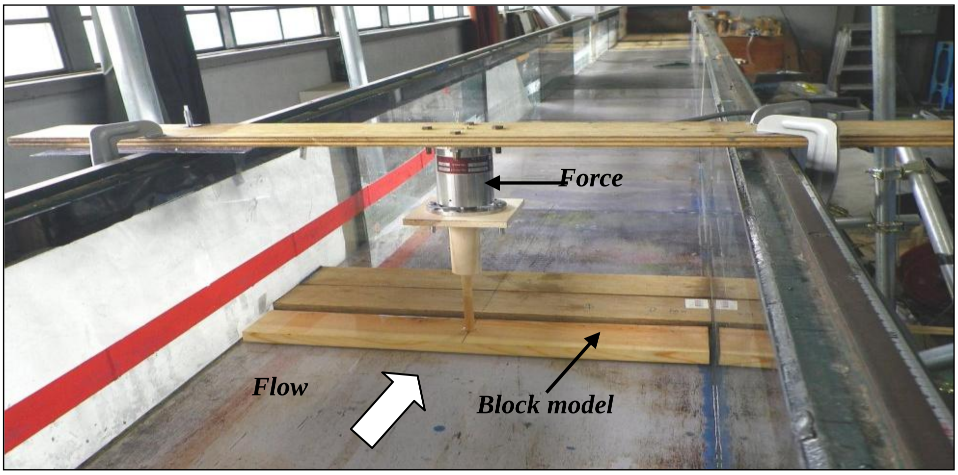


Fig.2.20. Set-up to measure lift and drag forces of scouring block.

2.8. Block (Refugia) stability analysis

The stability of the bed protection block in close relationship with drag force and lift force acting on the block were analyzed to understand the collapse condition of the block.

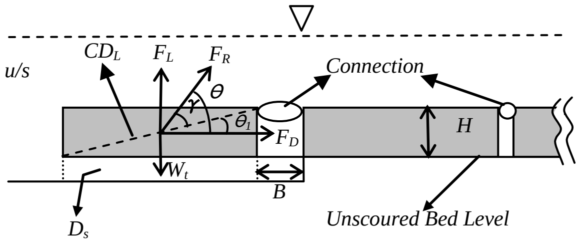


Fig.2.21. Analysis of the collapse condition of bed protection blocks

Fig.2.21 demonstrates the parameters of the bed protection block that were analyzed. In most practical cases, the bed protection blocks are connected to each other. The rotation center of acting moment was set as the point at the upper corner of block at the connection edge. The line that passes through the block's rotation center and its center of gravity (C.G.) is defined as the critical diagonal line (CD_L). The forces acting on the block are the drag force (F_D), lift force (F_L), and self-weight (W_t) of the block. The size of the angle (γ) made by the resultant force (F_R) on the CD_L defines the stability of the block for a flow condition. γ is determined by following formulae.

$$\gamma = \theta - \theta_1 \tag{9}$$

$$\theta_1 = \tan^{-1}(H/L_b) \tag{10}$$

$$\theta = \tan^{-1}((F_L - W_t)/F_D)) \tag{11}$$

Where, θ is the angle made by the resultant force on the block, θ_1 is the angle made by the CD_L on the block, H is the height of the block and L_b is the length of the block in the flow direction.

The bed protection block collapses if the angle (γ) between the resultant force and CD_L is between 0° to 160° (Inoue et al. (2009)).

CHAPTER 3

BEHAVIOR OF INVERTEBRATES WITH THE CHANGE IN APPROACH FLOW VELOCITY AND TURBULENCE

In this chapter the behavior of invertebrates with the change in approach flow velocity in a smooth bed (without roughness, WOR) and rough bed (with roughness, WR) is discussed. Critical depth averaged value, local velocity value for no walking and washout were calculated for without roughness (WOR) and with roughness (WR) cases. The effect of turbulence on invertebrate behavior of no walking and washout is clarified.

3.1. Velocity and turbulent intensity in the flume for cases of without roughness (WOR) and with roughness (WR)

The detail velocity was measured in the flume by electro-magnetic flow meter and PIV. The longitudinal velocity profile measured by electromagnetic velocity meter and velocity profile measured by PIV is shown in APPENDIX 2, APPENDIX 3, and APPENDIX 4. The turbulent intensity related to shear component (SC) and vertical component (VC) was calculated. Further, shear component and vertical component of turbulent intensity were analyzed spatially and locally as SC_S, VC_S, SC_L, VC_L (where subscripts 'S' denotes spatial and 'L' denotes local) (For definition see section 2.4). Figure 3.1 (a) shows the relationship between depth averaged velocity and VC_S for WR and WOR case. With the introduction of roughness, VC_S was increased by 15 and 37% for low and high flow conditions, respectively (Table 3-1). Similar trend could be observed for relationship between local velocity (near bed velocity) and VC_L as shown in Figure 3.1(b). The VC_L at around invertebrate height was not much increased (2.3%) for low flow conditions but was increased by 35% for high flow conditions (Table 3-1) by using the gravel roughness at upstream. Figure 3.1 (c) shows the relationship between depth-averaged velocity and SC_S for WR and WOR cases. With the introduction of roughness, SC_S was increased by 18% and 41% for low and high flow conditions (Table 3-1). Figure 3.1(d) shows the relationship between local velocity (near bed velocity) and SC_L. With roughness, SC_L at invertebrate height was not much increased (around 10%) for low flow conditions but was increased by 35% for high flow conditions (Table 3-1).

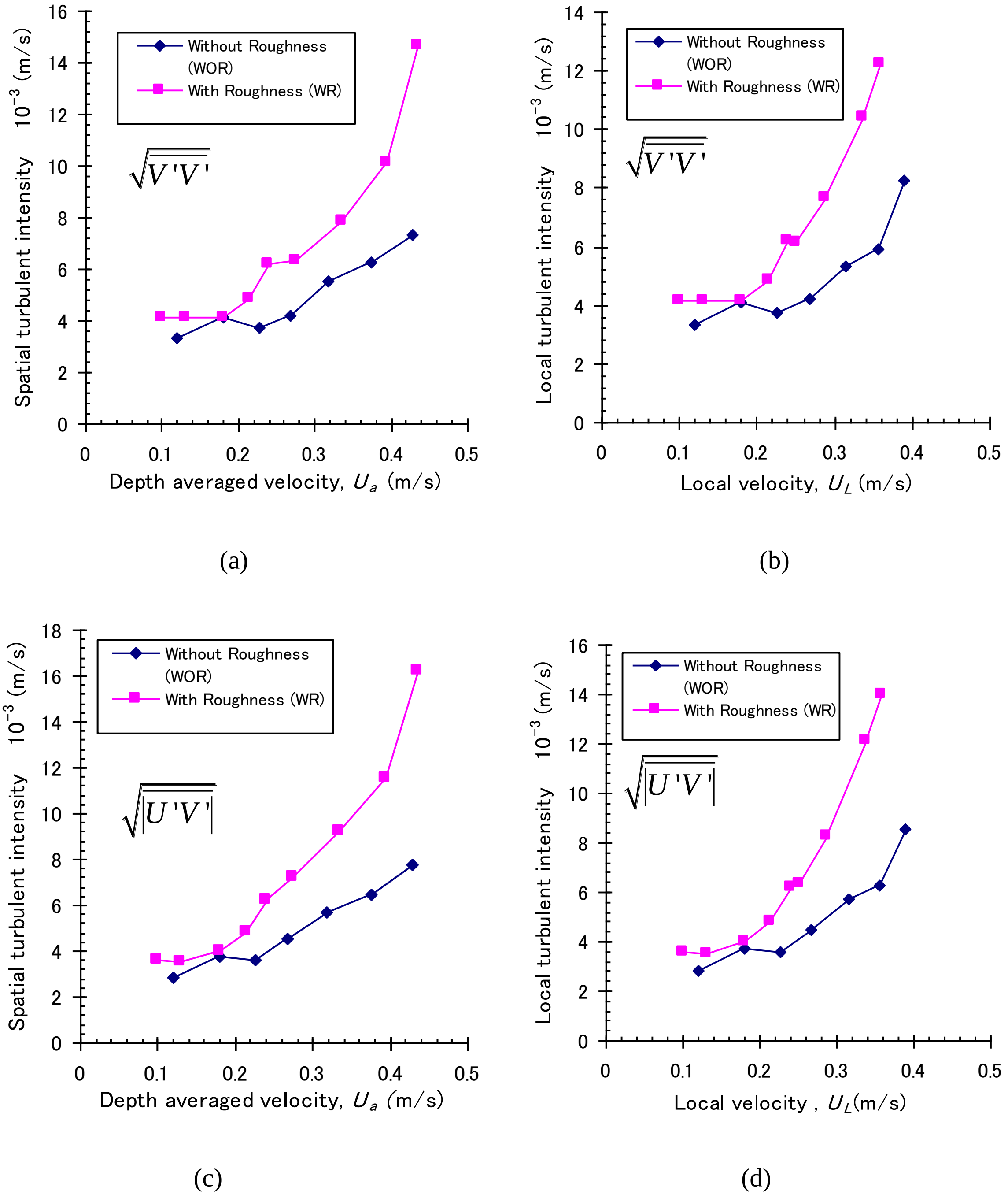


Fig.3.1. Comparison of the characteristics between the cases of roughness(WR) and without roughness (WOR) obtained from electro-magnetic velocity meter (a) depth averaged velocity and VC_S, (b) local velocity U_L (analyzed at 5mm distance from bottom which is roughly equal to invertebrate height) and VC_L, (c) depth-averaged velocity and SC_S, (d) local velocity and SC_L. For the definition of VC_S and SC_S, VC_L and SC_L see section 2.4.

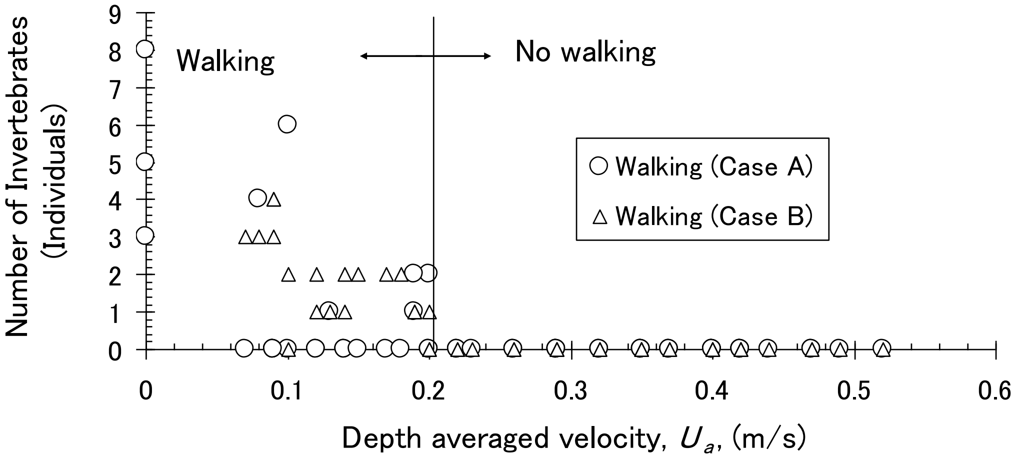
Table 3-1 Turbulent intensities during low flow condition (LFC) and high flow condition (HFC) for cases without roughness (WOR) and with roughness (WR)

		Without roughness (WOR)		With roughness (WR)	
Flow condition		LFC	HFC	LFC	HFC
Depth averaged velocity ,U_a (m/s)		0.2	0.4	0.2	0.4
Spatial turbulent intensity 10^{-3} (m/s)	VC_S	3.9	6.8	4.6	10.8
	SC_S	3.7	7.1	4.5	12.2
Local velocity, U_L (m/s)		0.18	0.25	0.18	0.25
Local turbulent intensity 10^{-3} (m/s)	VC_L	4.1	4	4.2	6.2
	SC_L	3.7	4.2	4.1	6.5

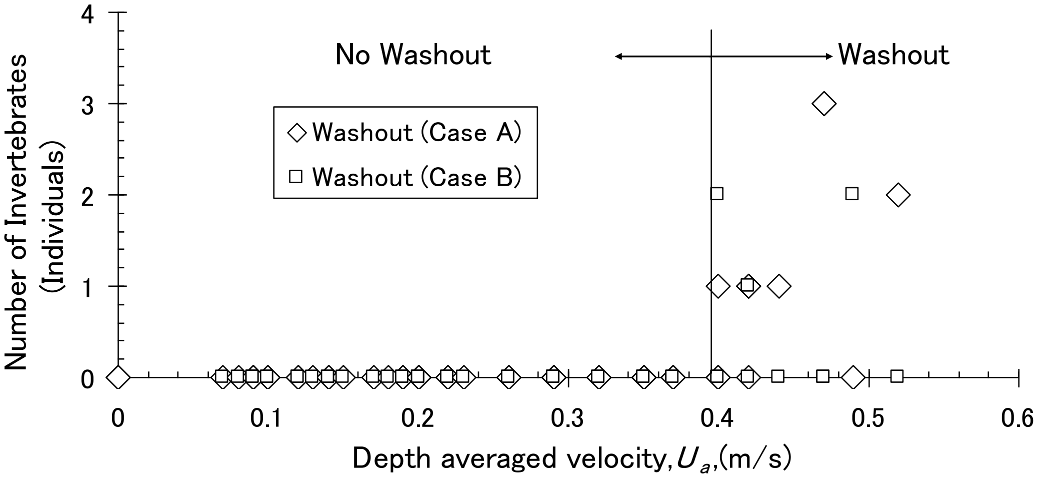
Note: Local velocity is calculated from PIV at 0.4cm depth from bottom bed surface and Local turbulent intensity is calculated from electro-magnetic flow meter at 0.5cm depth from bottom bed surface

3. 2. Invertebrate response to change in hydraulic condition (velocity) without roughness (WOR)

Fig. 3.2(a) shows the walking behavior of invertebrates for different depth averaged velocity for without roughness case (WOR). Initially, invertebrates were put inside the flume channel, and flow was directed from upstream towards the invertebrates. Invertebrates showed a quick response to the flow even though it was a weak flow. Invertebrates tired to endure the flow and started to find some comfortable places inside the flume. The most convenient place inside the flume without any refugia is the side wall region (Fig.2.2). So, when the flow started, the walking behavior of invertebrates was highly active. As the depth averaged velocity (U_a) gradually increased, the number of walking invertebrates was reduced as shown in Fig. 3.2(a). The active walking was observed when U_a was 0-0.2m/s. It was also noted that even for depth averaged velocity range of 0-0.20 m/s, the invertebrates mostly showed a high response to flow during incremental stage of velocity (Case B). It implies that when velocity is increased, the invertebrates that are already comfortable around their present location have to adjust to the new flow velocity. Invertebrates can do the adjustment by either making its body streamlined to flow or moving to another safer location. When the U_a reached 0.2 m/s, most of the invertebrates were at rest. We can assume that by this time, the invertebrates have already found the best possible position inside the flume because invertebrates completely stopped showing active walking behavior after U_a of 0.2 m/s. This, U_a of 0.2, is the critical depth averaged velocity value for no walking. Moreover, we can see in Fig. 3.2(a) that no walking could be seen from U_a of 0.2 - 0.4 m/s.



(a)



(b)

Fig.3.2. Critical value of depth-averaged velocity for invertebrate movement (Case WOR) (a) no walking and (b) for washout; (See Fig. 2.8 for definition of Case A and Case B)

We can see in Fig. 3.2(b) that after U_a of 0.4m/s, invertebrates were washed out from the flume channel for both uniform flow condition (Case A) and change in flow condition (Case B). This, U_a of 0.4, is the critical depth average velocity value for washout. At this stage, they need some kind of refuge (low shear stress area or low velocity area) because their best selected area is not good.

Irrespective of flow condition, without refugia, invertebrates endure all the time. However, endurance level depends on flow velocity. If the endurance level is low (small velocity i.e. U_a less than 0.2m/s), then invertebrates can walk very easily and actively. So, during no walking stage (i.e. U_a of 0.2-0.4m/s), the force generated by flow is under their endurance limit. But, when the U_a is more than 0.4m/s, invertebrates are enduring the force more than they can tolerate. So, invertebrates are washed out.

The local or regional velocity at the invertebrate height was analyzed from PIV experiment. The local velocity was calculated at 4 mm depth from the bottom (which is equal to the invertebrate height) for the corresponding critical depth averaged velocity for no walking and washout ($UC_{no\ walking}$ & $UC_{washout}$).The local critical velocity for no walking ($UCL_{no\ walking}$) and washout ($UCL_{washout}$) is around 0.12m/s and 0.22m/s respectively (Figs.3.3 , 3.4 & 3.5).

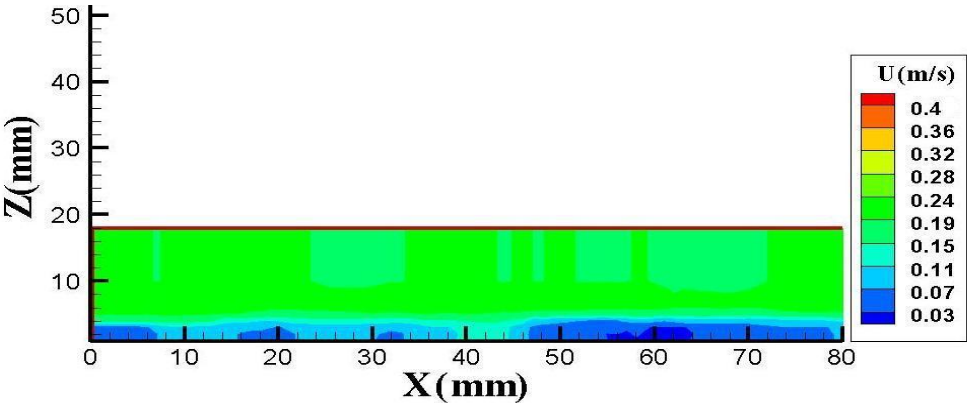


Fig.3.3. Velocity during low flow condition-without roughness (WOR) at X=0 (L_I = 90cm from inlet)- (water depth = 1.8cm & depth-averaged velocity = 0.20m/s); (See Fig.2.2); Invertebrate height is 4 mm.

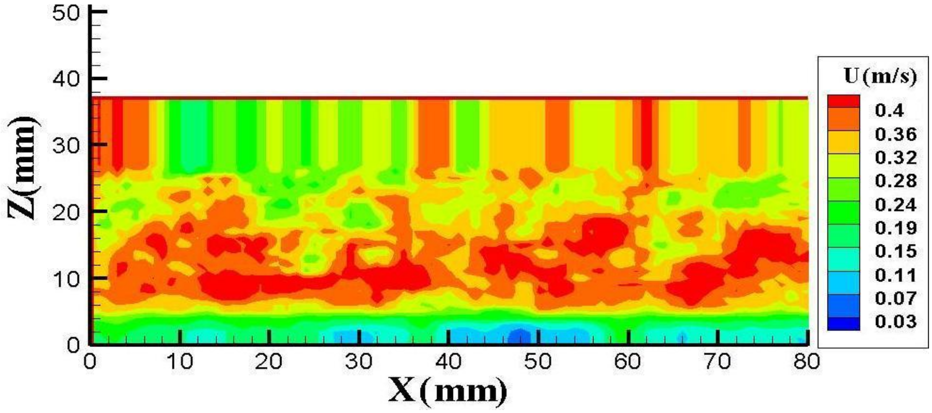


Fig.3.4. Velocity during high flow condition-without roughness (WOR) at X =0 (L_I = 90cm from inlet) - (water depth =3.8cm & depth-averaged velocity = 0.40 m/s); (See Fig.2.2); Invertebrate height is 4 mm.

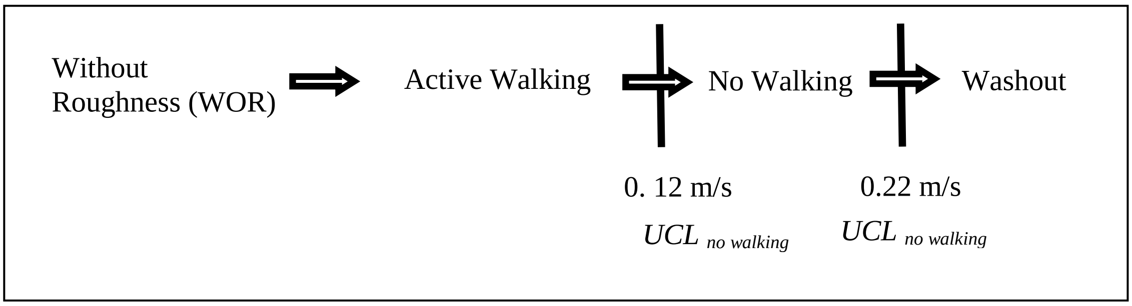
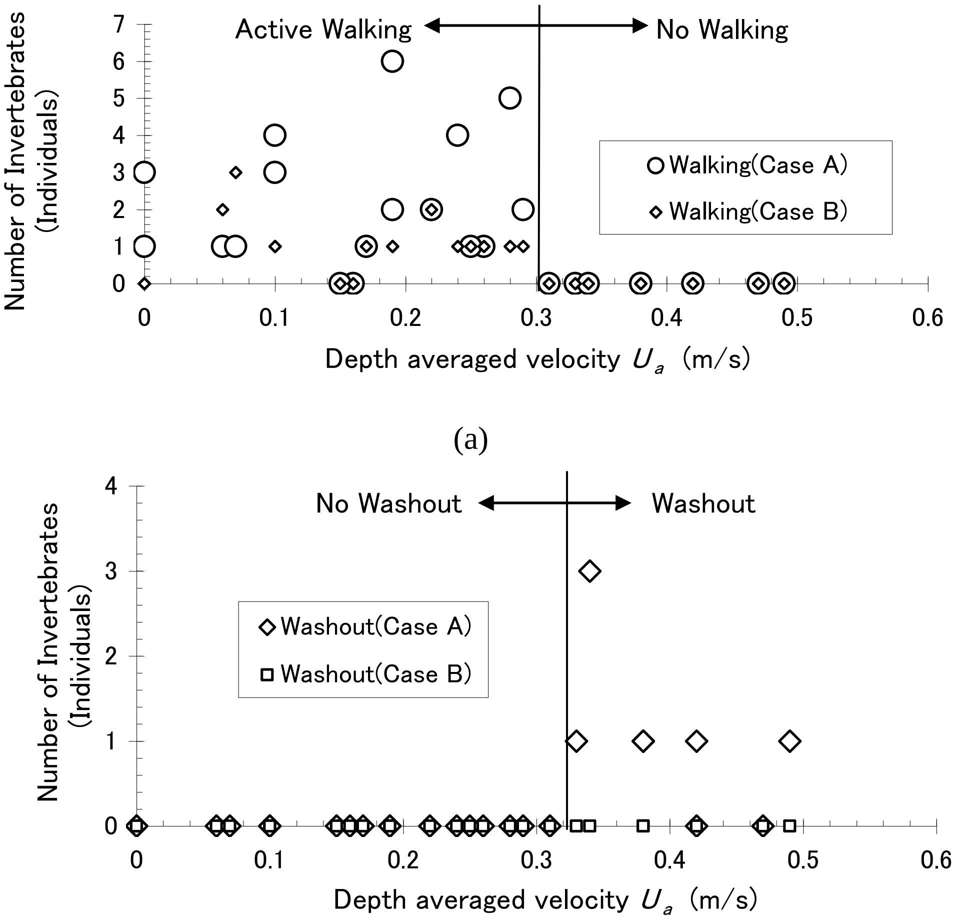


Fig.3.5. Summary for invertebrate's behavioral response to local velocity at invertebrate height: $UCL_{no\ walking}$ means local critical velocity for no walking and $UCL_{washout}$ means local critical velocity for washout) -without roughness (WR)

3. 3. Invertebrate response to change in hydraulic condition (velocity) with roughness (WR)

We can see in Fig.3.6 (a) that the movement behavior of invertebrate was very active for a depth averaged velocity (U_a) less than 0.30m/s. It was also observed that for Case A (uniform velocity stage) and Case B (incremental velocity stage) invertebrates showed active walking but for Case A (uniform velocity stage), more invertebrates showed active walking behavior. At U_a of 0 m/s (no flow condition), few invertebrates (3 individuals) showed active walking behavior and the number of invertebrates that showed active walking behavior increased with the increased flow condition. This type of trend happened till the depth averaged velocity of 0.10m/s. From U_a of 0.10-0.15m/s, invertebrates did not show movement inside the flume channel. Again after 0.15 m/s invertebrates showed active walking behavior and the number of invertebrates walking actively increased with the increased flow condition (velocity). Maximum movement of invertebrates (6 individuals) can be seen at a depth averaged velocity (U_a) of 0.18m/s. After U_a of 0.30m/s, again invertebrates stopped walking completely. This condition is the critical depth averaged velocity condition for no walking.



(a)

(b)

Fig.3.6. Critical depth-averaged velocity for movement behavior of invertebrates with roughness (WR) (a) no walking (b) washout; (See Fig. 2.8 for definition of Case A and Case B)

We can see in Fig.3.6 (b) that invertebrate (1 individual) is washed out from the flume at U_a of 0.33m/s. This condition is the critical depth averaged velocity for washout. Although, the washout rate does not increase with the increase in flow condition, invertebrates are washed out from the flume channel at regular interval (3 individuals at U_a of 0.34m/s, 1 individual at U_a of 0.38m/s, 1 individual at U_a of 0.42m/s, 1 individual at U_a of 0.48m/s). The result from this study for washout can be compared with the previous experimental study about the effects of different flow increase pattern (stepwise and abrupt) on the drift of invertebrate (Imbert and Perry 2000). They reported that peak drift was reached almost immediately in the abrupt flow increase and later in the stepwise increase treatment. However, this result shows that there is a peak for washout at the critical condition of washout and after that there is no further peak washout. The distribution of insect size or local velocity has a possibility to affect the study by Imbert and Perry (2000) in comparison with our controlled body size and velocity condition. Moreover, before the peak washout, invertebrates are not washed out. In addition, the invertebrates showed endurance pause at all depth-averaged velocities after no walking. The level of endurance was smaller when velocity was small and the level of endurance was higher when velocity was high.

3. 4. Discussion

3.4.1. Critical values for no walking and washout using depth averaged characteristics of flow

This experiment shows that an invertebrate behavior is greatly affected by approach flow velocity and turbulence. The results show that without roughness, the critical value of the depth-averaged velocities for no walking ($UC_{no\ walking}$) and for washout ($UC_{washout}$) is 0.20 and 0.40 m/s, respectively, for *Isonychia japonica*. Whereas, with roughness generating extra turbulence, the critical value of the depth-averaged velocities for no walking and washout are 0.3m/s and 0.33m/s, respectively, as shown in Table 3-2.

Table 3-2 Critical depth-averaged velocity and spatial turbulent intensities

Invertebrate behavior	No walking			Washout		
Bed roughness condition	WOR	WR	Turbulent intensity increment (%)TIPI	WOR	WR	Turbulent intensity increment (%)TIPI
Critical depth averaged velocity (m/s)	0.20	0.30		0.40	0.33	
Spatial turbulent Intensity 10^{-3} (m/s) VC_S:	3.9	7.0	44	6.8	7.8	12.8
Spatial turbulent Intensity 10^{-3} (m/s) SC_S:	3.7	8	53	7.1	9	21

Note: WOR-without roughness, WR- with roughness

In Table 3-2, critical depth averaged velocity, $UC_{no\ walking}$ of 0.3m/s for WR for no walking behavior of invertebrate is 33% larger than that of WOR case with 44% and 53% increase in VC_S and SC_S, respectively. This can be explained by the fact that although critical depth averaged velocity with turbulent intensity is increased for no walking of invertebrates; the invertebrate is strongly affected by the local velocity more than depth averaged velocity.

Likewise, the critical depth averaged velocity ($UC_{washout}$) of 0.33m/s for WR is 18% less than the $UC_{washout}$ for WOR (0.40 m/s) (Table 3-2). This can be explained by the fact that although VC_S is increased by 12.8%, SC_S for with roughness (WR) case is 21% higher than without roughness (WOR) case for washout(Table 3-2). So, it can be concluded that SC_S, parameter related to the shear or drag force acting on invertebrate, is far more effective in invertebrate washout than VC_S which is related to the lift force.

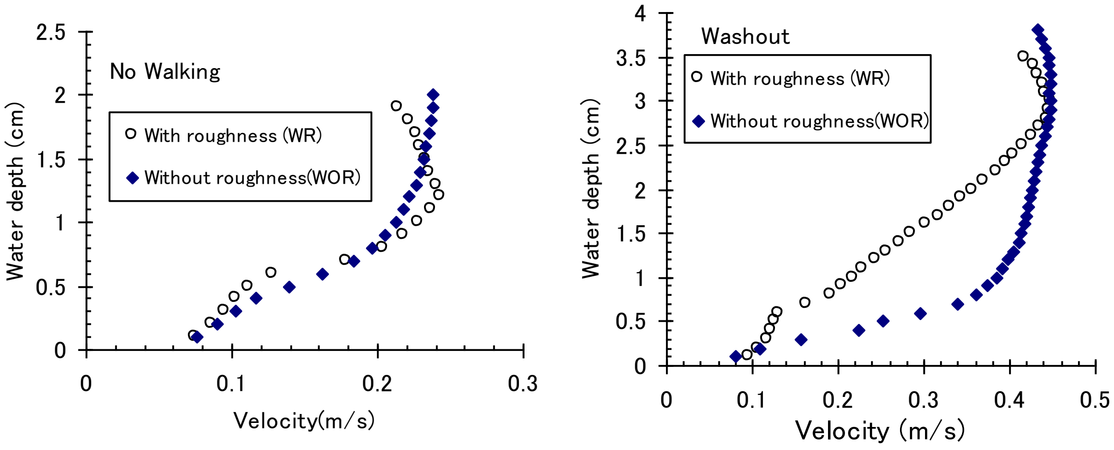
Robson et al. (1998) conducted field experiments with manipulated turbulence conditions. The manipulation caused the increase in turbulence intensity by 35% for a 20% reduction in velocity. They reported no significant effects on any aspects of the invertebrate assemblage. However, they speculated that the reason of such no significance would depend on the various limitations of the experimental conditions such as the degree of increase in turbulence intensity and turbulence tolerance of the invertebrate inhabit in the experimental reach. Although the detail of ambient turbulence did not measured in their study, the effect on invertebrate behavior could be seen from our result which alters the critical depth-averaged velocity for invertebrate's no walking and washout behavior.

3.4.2. Critical values for no walking and washout using local flow characteristics

The local velocity by PIV was obtained at 4mm distance from the bottom which is equal to the invertebrate height (4mm average). The local critical velocity for no walking ($UCL_{nowalking}$) and washout ($UCL_{washout}$) is 0.12m/s and 0.22m/s respectively for without roughness (WOR) case (Figs. 3.3,.34 ,3.7(a) and (b)). When turbulence is introduced, $UCL_{nowalking}$ and $UCL_{washout}$ is 0.1 m/s and 0.12 m/s respectively (3.7(a) and 3.7(b)).

Comparing without roughness (WOR) case where $UC_{no\ walking}$ is 0.2m/s, $UC_{no\ walking}$ for roughness (WR) case is higher (0.3m/s) (Table 3-2). But local critical velocity of no walking ($UCL_{nowalking}$) for roughness (WR) case (0.1 m/s) is lower compared to that of without roughness (WOR) case (0.12 m/s) (Table 3-3). Even though local velocity is similar for both cases, the velocity gradient at invertebrate height for WR case is smaller during critical no walking behavior. The velocity gradient for WOR case is 20 s^{-1}, where as for WR case is 10 s^{-1}. So, for WR case, velocity difference above and below invertebrate body height is smaller. As a result, lift force acting at invertebrate body is also smaller. This is the reason why invertebrates can withstand and walk even at larger depth averaged velocity compared to WOR case. This also concludes that local velocity is more important than depth-averaged velocity for understanding invertebrate behaviors. Moreover, VC_L and SC_L, at invertebrate height during critical no walking behavior for without roughness (WOR) case is $3.3x10^{-3}$m/s and $2.8x10^{-3}$m/s respectively (Table 3-3). Likewise, VC_L and

SC_L, at invertebrate height during critical no walking for with roughness (WR) case is 4.1×10^{-3}m/s and 3.6×10^{-3}m/s respectively. So, we can clearly see that when roughness is introduced, at invertebrate height level, VC_L and SC_L are increased by 19.5 % and 22 %, respectively. Although both VC_L and SC_L are effective, comparatively, SC_L which acts along their body is more responsible for invertebrate no walking behavior.



(a) (b)

Fig.3.7. Velocity profile for without roughness (WOR) case and with roughness (WR) case (a) no walking (b) washout; velocity profile for washout is from the washout location of invertebrate inside the flume.

Table 3-3 Local critical velocity and Local turbulent intensities

Invertebrate behavior	No walking			Washout		
Bed roughness condition	WOR	WR	Turbulent intensity increment (%)TII	WOR	WR	Turbulent intensity increment (%)TII
Local critical velocities (m/s)	0.12	0.10		0.22	0.12	
Local turbulent Intensity 10^{-3} (m/s) VC_L	3.3	4.1	19.5	3.8	4.1	7.3
Local turbulent Intensity 10^{-3} (m/s) SC_L:	2.8	3.6	22	3.5	3.6	2.8

Note: WOR-without roughness, WR- with roughness

Similarly, $UCL_{washout}$ for WR case (0.12 m/s) is lower compared to $UCL_{washout}$ for WOR case (0.22 m/s). For washout behavior, invertebrates are more affected by upstream roughness because invertebrates are washed out at smaller velocity due to the higher local turbulence. Local turbulent intensities, VC_L and SC_L, at invertebrate height during critical washout for without roughness (WOR) case is $3.8x10^{-3}$m/s and $3.5x10^{-3}$m/s respectively (Table 3-3). Likewise, VC_L and SC_L, at invertebrate height during critical washout for with roughness (WR) case are $4.1x10^{-3}$m/s and $3.6x10^{-3}$m/s respectively. So when roughness is introduced, VC_L and SC_L are increased by 7.3% and 2.8%, respectively. So, VC_L, parameter that is assumed to be related to the lift force acting on invertebrate has a possibility to affect more for washout. It can further explained from velocity gradient at invertebrate height. The velocity gradient for without roughness (WOR) case is 60 s^{-1}, where as for with roughness (WR) case is 10 s^{-1}. The velocity gradient at invertebrate height for with roughness (WR) is smaller during critical washout behavior. So, it can be assumed that shear force acting on invertebrates is smaller when there is roughness during washout and although shear force is larger for WOR case, invertebrate are washout at higher local velocity than WR case. So, it can be concluded that SC_L is not dominant, whereas VC_L can be considered dominant for washout of invertebrates under rough bed condition. Moreover, *Isonychia japonica* used in this study took enduring pause before washout. This is supposed to reduce the lift force component because the force is related to the pressure difference of upper and lower part of the body. By the enduring pause, it has a possibility to reduce the effect of $VC_{L,}$, however, the effect of increasing VC_L is large So, the VC_L is more dominant force for washout.

If local velocity is used for analyzing invertebrate behavior, then the result from this study seems to contradict with the results obtained by Gibbins et al.(2010). They concluded that shear stress was more important in causing drift in *Ecdyonurus* and *Baetis*, while for *Caenis* both shear and bed disturbance were equally important. However, when we consider depth averaged velocity like section 3.4.1, it can be concluded that shear force is responsible for washout of invertebrate (Table 3-2).

The results from this study show that it is possible to manipulate the turbulent intensity in small scale flume experiment. VC_L and SC_L in this study were 0.4-1.2cm/s and 0.35-1.40cm/s, respectively, at a local velocity of 10-36cm/s. These values are lower than those recorded by Bouckaert and Davis (1998) for wakes behind the boulders using ADV in a slow lowland stream, which recorded average streamwise turbulent intensities of 1.7-2.5cm/s at a mean velocity of 10-15cm/s. A different method would be needed to increase turbulence levels above those measured in this study. One method is to increase the artificial roughness length (90 cm in this study). Another method is to increase the roughness height (4 mm in this study). However, the roughness height more than 4mm would act as a refuge for invertebrates. Robson et al. (1999) explained that there was absence of a response in the invertebrates for increased turbulence at each of his sites because invertebrates are tolerant of turbulent flow. They conducted their experiment in a stream, so even if some turbulence is applied, the effect could be minimal due to some other factors such as invertebrate's sheltering around refugia. Since our experiment did not provide refugia together with the roughness, the effect of turbulence affecting invertebrate behavior of critical velocity has been clearly seen.

3.4.3. Importance of the experiment without refugia and controlled velocity condition for clarifying invertebrate behavior

Refugium is also an important parameter in affecting the behavior of invertebrates along with the turbulence. Bouckaert and Davis (1998) discussed about the benthic macro invertebrates abundance in the wake than at the front boulders. They also found that near bed velocities were greatly reduced in both the front and wake regions. Although, we did not consider the behavior of invertebrates with refugia for this study, requirement of refugia can be discussed briefly. In this study, from start of flow in the flume channel, invertebrates start walking (Figs 3.2 and 3.6). This either means that they can walk easily or they need some kind of refugia. They went to flume channel wall area from central area to avoid fast current flow. This means that if refugia such as small boulders were provided then invertebrates would not have gone to wall area. Moreover, behavior such as washout may not be seen when some refugia exist and the effect of turbulence could be less than that of the results obtained from this study. During high flows ($U_a \geq 0.33$ m/s), it was observed that they desperately needed refugia but since there was none; they were washed out from the flume channel. From the experimental setup in this study, the critical conditions of flow velocity in relation to turbulence have been clarified.

Ciborowski (1983a) showed that mayfly nymphs drifted shorter distances and McLay (1970) found that invertebrates were dislodged to a mean distance of 0.5 to 19.3m for a velocity of 0.21m/s. However, in this study, at 0.21m/s, invertebrates were not dislodged. Invertebrates were dislodged at 0.40m/s in smooth bed condition and 0.33m/s in rough bed condition. Moreover, the distance of invertebrates after dislodgement was greater than 90cm. The correlation between current and drift (dislodgement) of invertebrates can be explained in number of ways. As explained by Mackay and Kalff

(1973), Ciborowski (1983b) that the increase in water velocity increases the shear stress and thus can increase the chance of dislodgement when invertebrates are active, as well as resting at shelters. However, in this study, the dislodgement rate did not increase with the increase in velocity. Moreover, it was observed that after certain critical velocity, invertebrates are not active and at certain critical velocity, invertebrates are dislodged. This result is more or less similar to the results obtained by Corkum et al. (1977). Their result has shown that the drift (dislodgement) of *Baetis nymphs* decreases with increasing velocities. The dislodgment trend in this study and the trend explained by Corkum et al. (1977) could be true if the substratum is fairly stable. Under poor substratum, the drift rate could increase with the increment of velocity. Moreover, the effect of the release of an artificial discharge of water on invertebrate drift has been explained by Brooker and Hemsworth (1978). Their result suggests that the incremental flow resulted in increase of drift densities of *Ephemerella ignita*. Although the experiment at night was not conducted, the incremental flow and uniform flow in this study equally affect the washout (dislodgement) of *Isonychia japonica* (*Ephemerella* family) (Fig. 3.2(b)). However, with the introduction of roughness at upstream, in this study, the incremental flow doesn't have an effect on washout (dislodgement) of the invertebrates (Fig. 3.6(b)).

Table 3-4 Critical values of shear stress, depth-averaged velocity and local velocity for no walking and washout

Invertebrate behavior	No walking		Washout	
Bed roughness condition	WOR	WR	WOR	WR
Critical shear stress , τ_c (N/m^2)	0.14	0.065	3.41	0.12
Critical depth averaged velocity, U_a (m/s)	0.20	0.30	0.40	0.33
Critical local velocity, U_L (m/s)	0.12	0.10	0.22	0.12

Note: WOR-without roughness, WR- with roughness

The bed shear stress was calculated using the law of the wall formula (Kundu and Ghoshal, 2012). The extra turbulence generated by upstream roughness increases the critical bed shear stress for no walking and washout behavior of invertebrate (as shown in Table 3-4). Gibbins et al.(2007) also showed the existence of the critical shear stress that invertebrates (mayflies Baetis, *Ecdyonurus*, Caddisflies of family *Hydropsychidae*) drift or dislodgement in a flume with gravel bed began to increase at a greater rate once the shear stress reached a values of approximately 9 dynes/cm^2 (0.9 N/m^2). Our study further indicates the critical value is changed with critical local velocity and turbulence that *Isonychia japonica* starts to dislodge at a shear stress of 3.41 N/m^2 (without roughness) and 0.12 N/m^2 (with roughness).

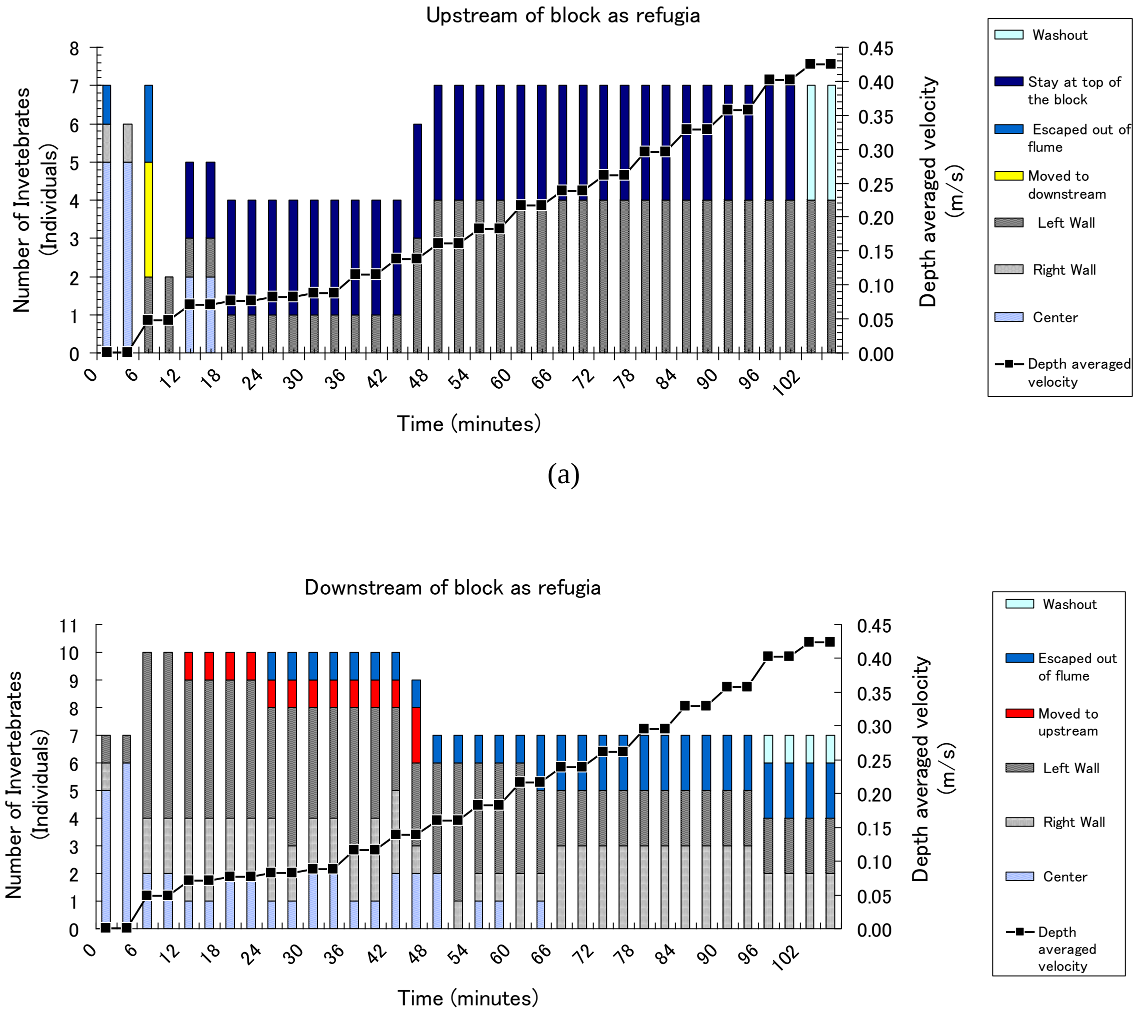
CHAPTER 4

EFFECT OF BLOCK FOR REFUGIA ON INVERTEBRATES AND ITS STABILITY

In this chapter, the importance of refugia in improving the hydraulic condition for invertebrate has been discussed. Moreover, the flow pattern around refugia, pressure around refugia and drag and lift acting on refugia and the stability of refugia has also been analyzed.

4.1. Single block as refugia (Case M1)

In the beginning of the experiment, the single block (Case M1) as refugia was provided (See Fig.2.13for block arrangement). We can see in Fig. 4.1 (a) that initially, 5 number of invertebrate was present at center of flume (CA), 1 at left wall (LWA) and 1 at right wall (RWA),(refer Fig.2.2 for definition of CA, LWA and RWA). When the flow started invertebrates started to move inside the flume channel. They changed their position from center to left wall or left wall to center, right wall to left wall or left wall to right wall, center to right wall or right wall to center. As the velocity increased, some invertebrates went to downstream of block and some escaped out the flume channel from upstream side towards the inlet. It can seen in the Fig. 4.1(a), upstream of block, that 3 individuals went to downstream of block and 2 individuals escaped out of flume at a depth averaged velocity of 0.05m/s. Similarly some invertebrates come to upstream of block from downstream of block. When the velocity increased more, 4 individuals of the invertebrates were located at the left wall of block’s upstream and 3 individuals were at the top of block. At a depth averaged velocity of 0.40m/s, 3 individuals were washed out of flume from upstream of block. So, It can be said from this observation that upstream side of block did not provide good refugia. Likewise, at the downstream of block (Fig. 4.1(b)), invertebrates started to move from start of flow inside the flume channel. At a depth average velocity of 0.10m/s, some invertebrates went to upstream side of block by crawling and crossing the block. The invertebrates stayed in the center of flume channel for a depth average velocity of 0.25m/s. After the depth averaged velocity was increased more than 0.25m/s, invertebrates moved to right wall from center position and stayed there till the depth averaged velocity reached 0.35m/s. From depth averaged velocity of 0.40m/s, invertebrates were washed out the flume. Finally, the number of invertebrate remains inside the flume channel was 4 individuals. Out of them, 2 individuals are located at left wall and 2 individuals at right wall. Since the invertebrates did not take refuge behind the block, instead take refuge at left wall or right wall, we can conclude that downstream of block did not provide good refuge for invertebrates



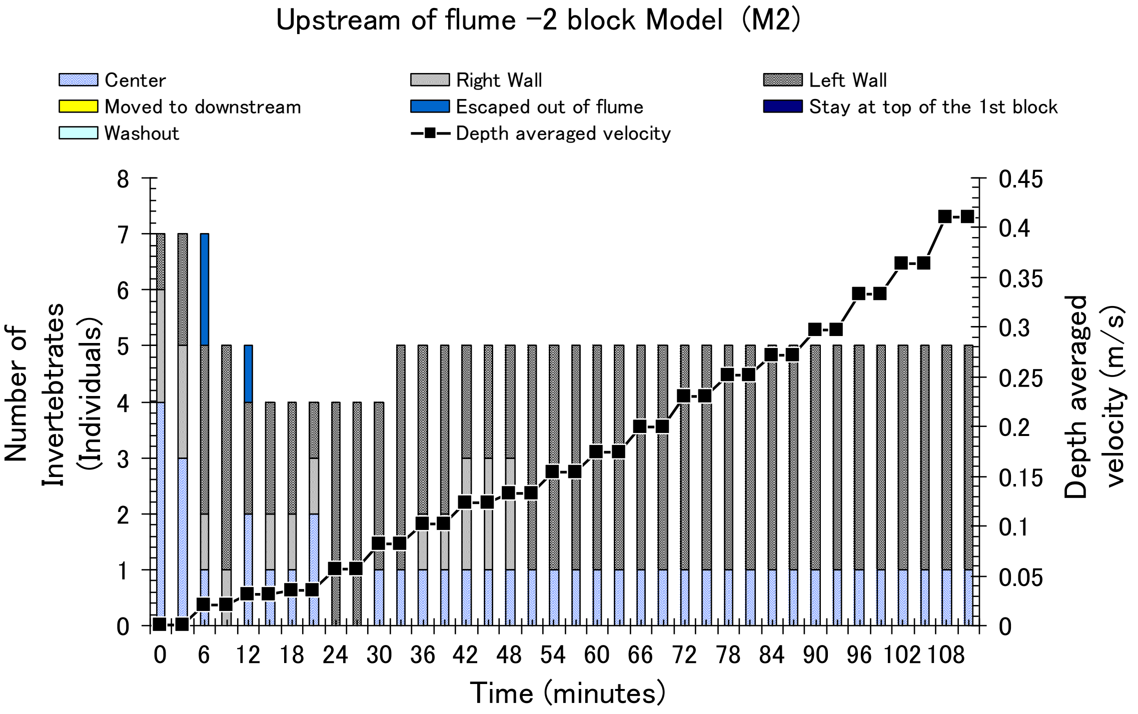
(a)

(b)

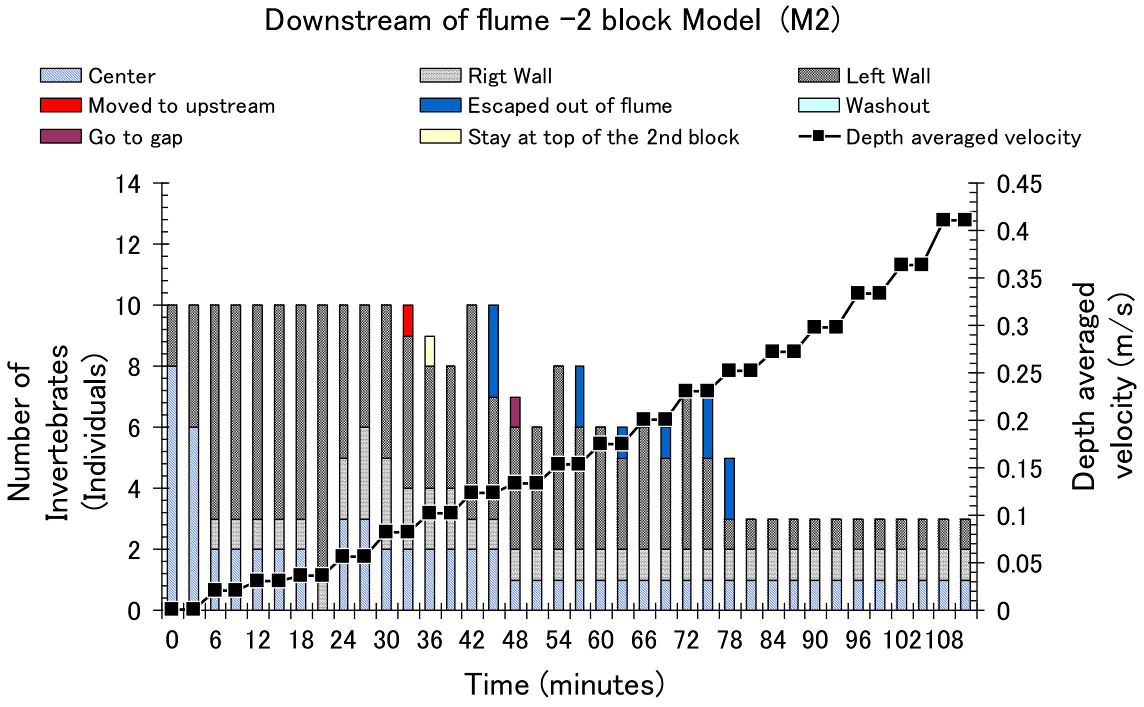
Fig.4.1. Single block as refugia (Case M1) and their washout, escape, position inside flume with time (a) upstream of block (b) downstream of block ; Left Wall refers to the invertebrates at left wall area (LWA), Right Wall refers to the invertebrates at right wall area (RWA), Center refers to the invertebrates at center area (CA).

4.2. Double block as refugia (Case M2)

The invertebrate position in the flume channel at upstream of 1st block (Zone *U*), downstream of 2nd block (Zone *D*), in-between 1st block and 2nd block (Zone *B*) for double block as refugia (Case M2) has been shown in Fig. 4.2 (a), 4.2 (b) & 4.2 (c).



(a)



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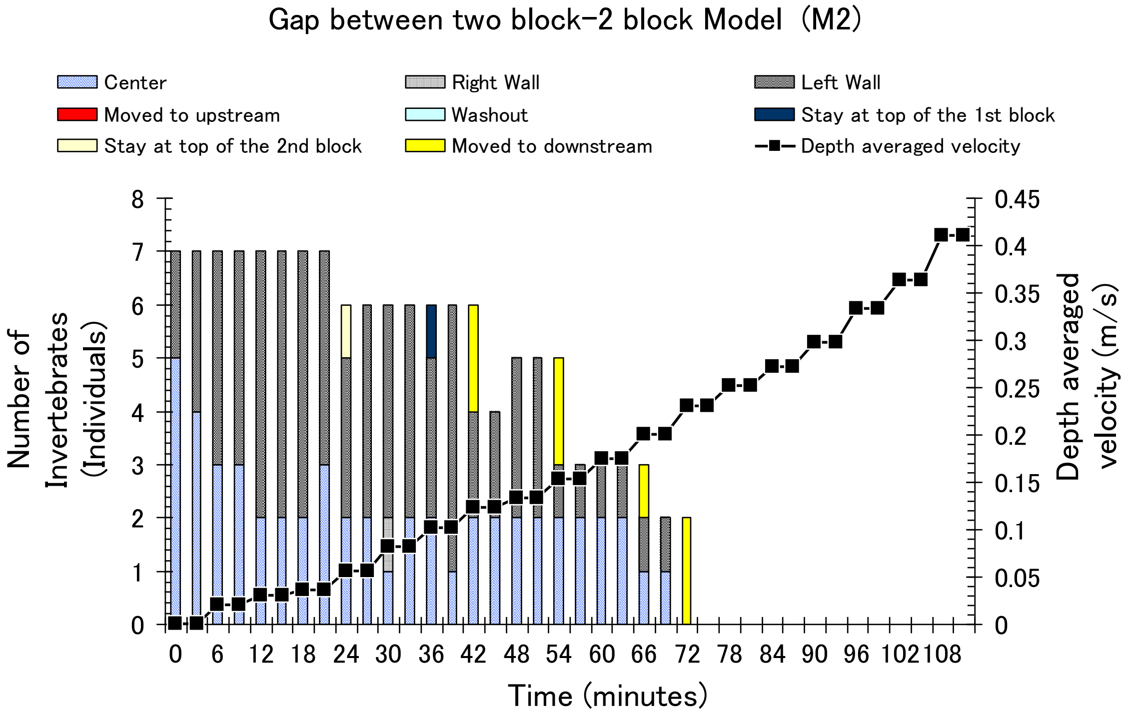


(c)

Fig.4.2. Double block as refugia (Case M2) and their movement, position inside flume with time-observation (a) upstream of 1st block (Zone U) (b) downstream of 2nd block (Zone D) (c) in between 1st block and 2nd block (Zone B); Left Wall refers to the invertebrates at left wall area (LWA), Right Wall refers to the invertebrates at right wall area (RWA), Center refers to the invertebrates at center area (CA).

It can be seen in Fig. 4.2 (a) that number of invertebrate at center (CA), right wall (RWA) and left wall (LWA) were 4, 2 & 1 individuals respectively at upstream of 1st block (*Zone U*). As the flow started, velocity increased inside the flume channel and invertebrates moved actively. As the velocity increased more, few (2) invertebrates escaped from flume, few went to wall side and the rest of the invertebrates stay at center. They mostly went to left wall (LWA). This can be explained by the fact that wall area provided as refuge to invertebrates than central area (CA).

It can seen in Fig. 4.2 (b) that number of invertebrate at center (CA) and left wall (LWA) were 8, 2 respectively at downstream of 2nd block (Zone *D*). It was observed that invertebrate moves to left wall and right wall area as the flow started but more number of invertebrates gathered in left wall area. At a depth averaged velocity of 0.08m/s, 1 invertebrate went to upstream, Zone *U*. When U_a was 0.1m/s, 1 individual moved to top of

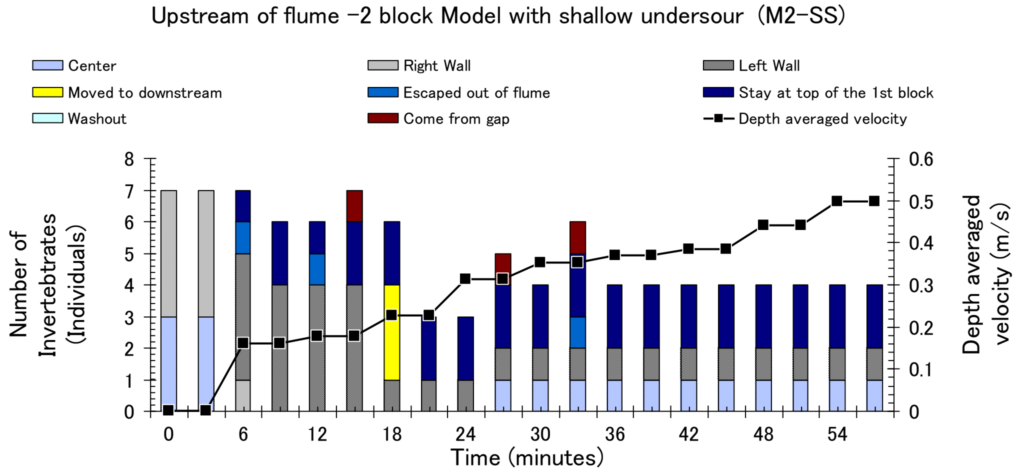
2nd block and at U_a of 0.13m/s, 1 individual moved to Zone B. The number of invertebrates inside Zone *D* decreased due to invertebrates escaping out of flume. 1, 1, 2 and 2 individuals escaped out of the flume at U_a of 0.17, 0.20, 0.23 and 0.25m/s respectively. After depth averaged velocity, U_a, of 0.25m/s, invertebrates did not move and remain at the same position.

It can be seen in Fig. 4.2 (c) that number of invertebrate at center (CA) and left wall (LWA) were 5, 2 individuals respectively in-between 1st block and 2nd block (Zone *B*). The flow was started and velocity increased in the flume channel. The invertebrate gradually moved to left wall (LWA) of the flume from center (CA). At a U_a of 0.06m/s, 1 individual went to top of 2nd block and at U_a of 0.10, 1 more individual went to top of 1st block. The invertebrate at the top of 2nd block moved back to Zone *B*. The invertebrate at the top of 1st block moved back to gap at same U_a of 0.10m/s. Then at U_a of 0.12, 0.15, 0.20 and 0.23m/s, 2, 2, 1 and 2 individuals respectively went to downstream Zone (Zone *D*). From U_a of 0.25m/s, no individuals remain inside the gap So, we can finally conclude that two block refugia setup without underscouring is not suitable for refugia based on the number of invertebrates remain at Zone *U*, Zone *D* and Zone *B*.

4.3. Double block with shallow underscour as refugia (Case M2-SS)

The double block with shallow underscour beneath the first block (Case M2-SS) was used as refugia. The invertebrate position in the flume channel at upstream of 1st block (Zone *U*) , downstream of 2nd block (Zone *D*) , in-between 1st block and 2nd block (Zone *B*) for double block with shallow underscour as refugia (Case M2-SS) has been shown in Fig. 4.3 (a), 4.3 (b) & 4.3 (c). Although 7 individuals were put at center, invertebrates already moved without the start of inflow. We can see in Fig. 4.3 (a), upstream of first block, that number of invertebrate at center and right wall are 3 & 4 individuals respectively at upstream of 1st block (Zone *U*). As the velocity increases, most of the invertebrate moves to left wall. From, depth averaged velocity, U_a of 0.15-0.30m/s no individual remains at center and right wall. 1 individual remain at left wall from U_a of 0.23m/s. At, U_a of 0.35m/s, 1 individual come from gap (Zone *B*). After, U_a of 0.35m/s, invertebrate doesn’t show walking movement inside the flume. 1 individual of invertebrates escaped at U_a of 0.16, 0.18, and 0.35m/s. 1 individual come from gap at 0.35m/s. invertebrates (2 individuals) went to top of 1st block at U_a of 0.16m/s and again 1 individual went to top of 1st block at U_a of 0.18m/s

Although 7 individuals were put at center, invertebrates already moved without the start of inflow. It can be seen in Fig. 4.3 (b), downstream of second block, that invertebrate (4 individual at right wall, 1 individuals at center and 2 individuals at left wall) were located at center just behind the block at no flow condition. As the velocity increased, some invertebrates (2 individuals) escaped out the flume, some invertebrates (2 individuals) moved to from right wall to left wall, 1 individual at center to left wall. The invertebrates moved and changed their position for a depth averaged velocity, U_a of 0-0.31 m/s. we can see that at this velocity, 1 individual go to top of 2nd block and 1 individual escaped from flume at U_a of 0.18m/s. Finally, 2 individuals remain at left wall and 2 individuals remain at right wall.



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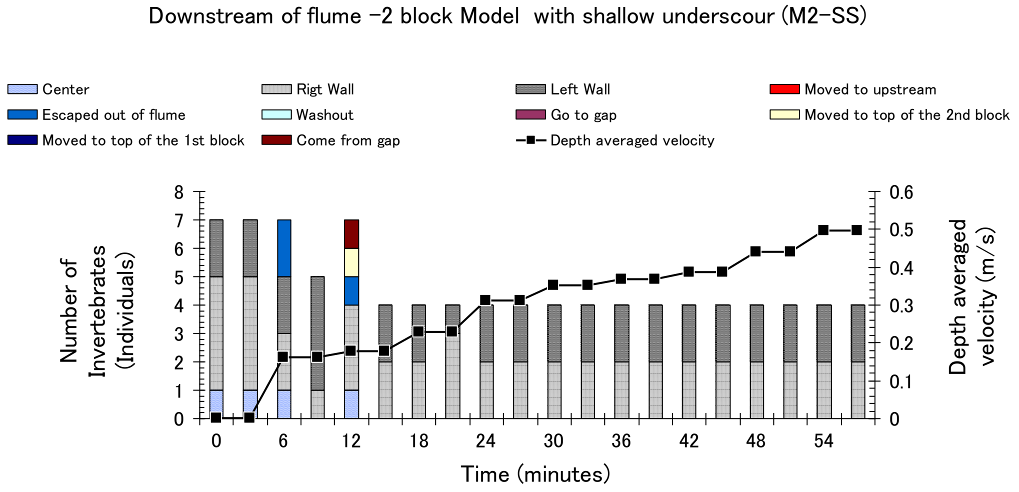

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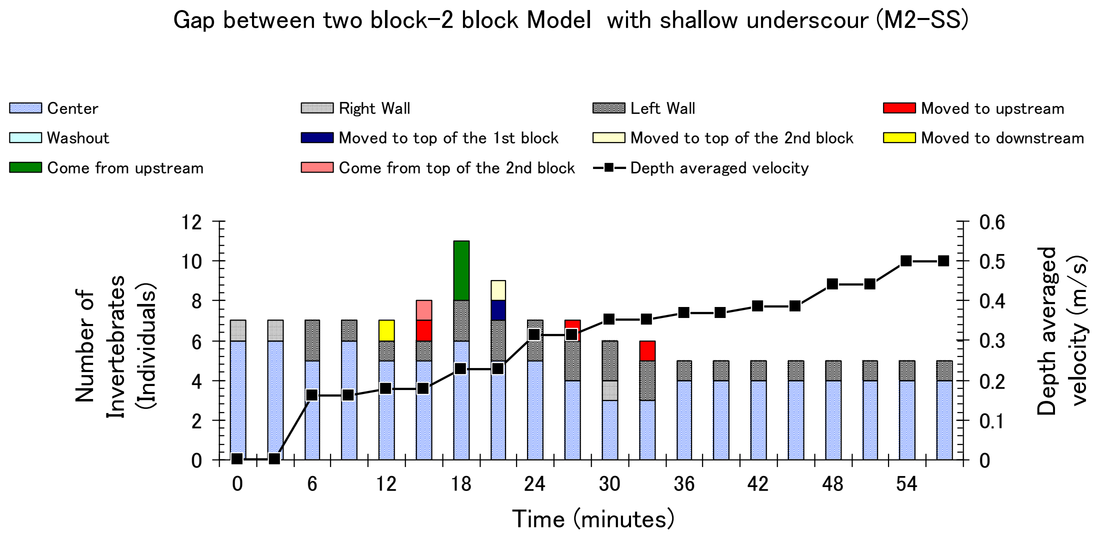


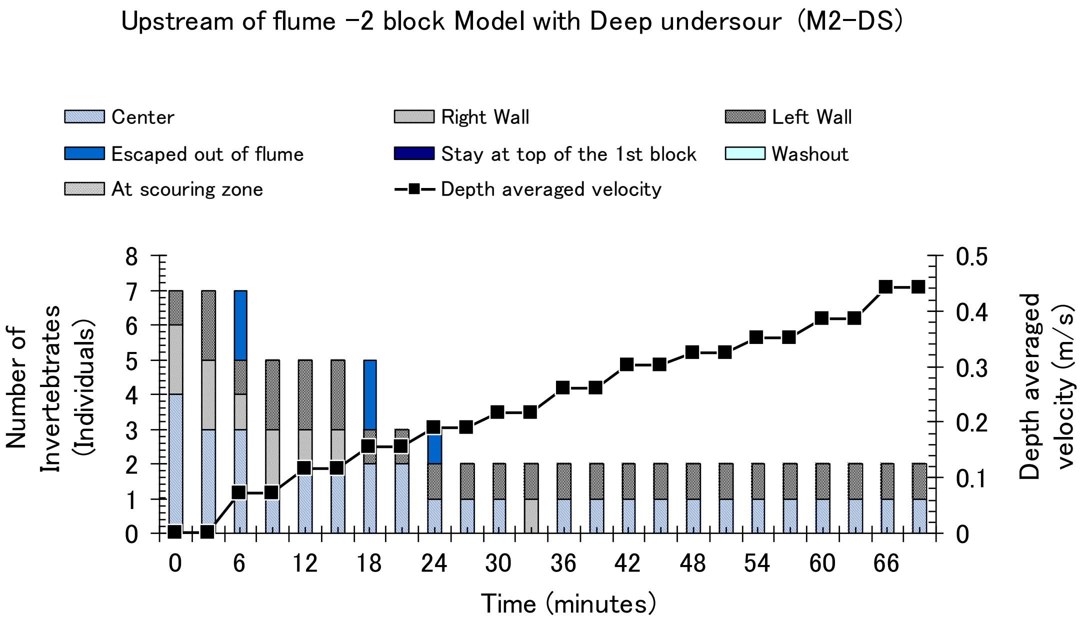
(c)

Fig.4.3. Double block as refugia with shallow underscour (Case M2-SS) and their movement, position inside flume with time- observation (a) upstream of 1st block (Zone U) (b) downstream of 2nd block (Zone D) (c) in between 1st block and 2nd block (Zone B); Left Wall refers to the invertebrates at left wall area (LWA), Right Wall refers to the invertebrates at right wall area (RWA), Center refers to the invertebrates at center area (CA); the number shows the total number of invertebrates in flume left wall, right wall and center.

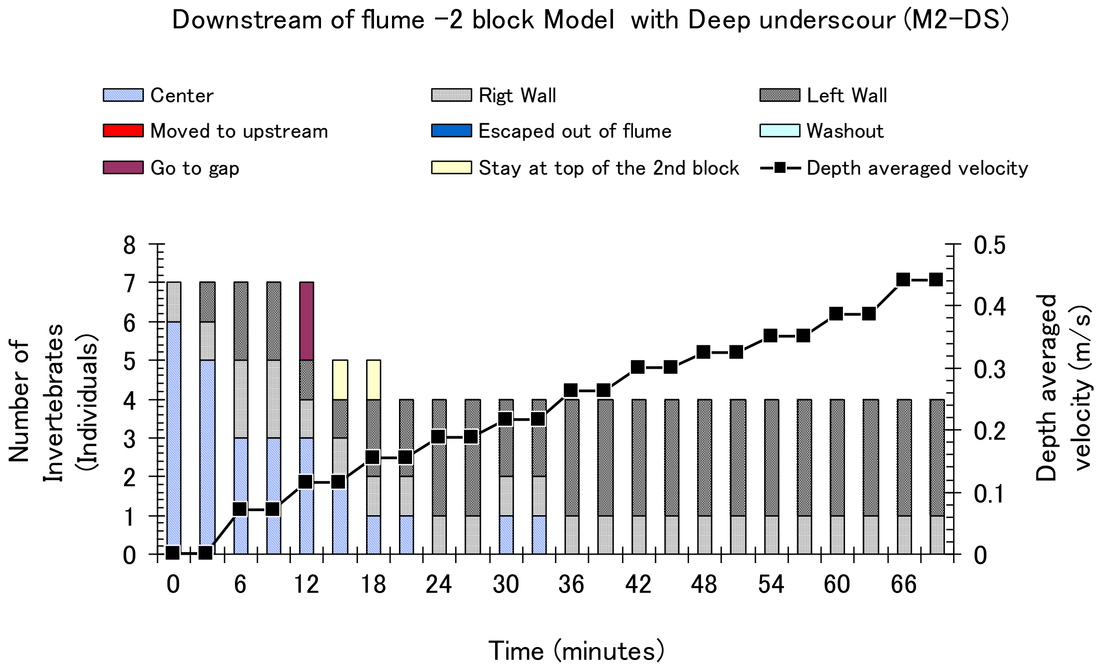
It can be seen in Fig. 4.3 (c), inside the gap (Zone *B*) between 1st block and 2nd block, that most of the invertebrate (6 individuals) were located at center just behind the block and 1 individual was at right wall at no flow condition. Although, the flow started, invertebrates didn't seem to move much across the flume like the case in Zone *D* and Zone *U*. One of the reasons could be that at the Zone *B*, the flow condition is favorable to invertebrates. Although 1 individual moves to downstream zone (Zone *D*) and another moves to upstream zone (Zone *U*) at a depth average velocity (U_a) of 0.18m/s, 3 individuals come from upstream (Zone *U*) at a depth average velocity (U_a) of 0.23m/s. The invertebrate going to Zone *D* and Zone *U* is mainly due to congestion in small gap with so many invertebrates. Although 3 individuals come from Zone *U*, they quickly go to top of 1st block and top of 2nd block. At, a depth average velocity, (U_a) of 0.18m/s, 0.31m/s and 0.35m/s, invertebrate go to upstream (Zone *U*). After, U_a of 0.37m/s, 4 individuals remain at center of gap (Zone *B*) and don't show any movement high flow conditions too. So, from this observation we can conclude that although downstream zone (Zone *D*) doesn't provide any refugia. However, the gap (Zone *B*) and upstream zone (Zone *U*), clearly provides some refugia.

4.4. Double block with deep under scour as refugia (Case M2-DS)

The invertebrate position in the flume channel at upstream of 1st block (Zone *U*) , downstream of 2nd block (Zone *D*) , in-between 1st block and 2nd block (Zone *B*) for double block with shallow underscour as refugia (Case M2-SS) has been shown in Fig. 4.4 (a), 4.4 (b) & 4.4 (c). We can see in Fig. 4.4 (a) that number of invertebrate at center (CA) , left wall (LWA) and right wall (RWA) are 4, 1, & 2 respectively at upstream of 1st block (*Zone U*).In this case also, at Zone *U*, invertebrates change their position , some escape out of the flume channel when velocity is increased. Invertebrates were at center and left wall during high flow conditions. At Zone *D*, Fig. 4.4 (b), invertebrate was not at all present at center (behind the block) during high flow conditions (U_a > 0.25m/s). Invertebrate (2 individuals) went to gap (Zone *B*), invertebrate (1 individual) went to top of 2nd block at U_a of 0.12m/s. At U_a of 0.12m/s, 1 invertebrate escaped out of the flume. Although, more invertebrates (4 individuals in total) were present at Zone *D* (compared to Zone *U*) due to less escaping by invertebrates from flume channel, no individual remained at the center.



(a)



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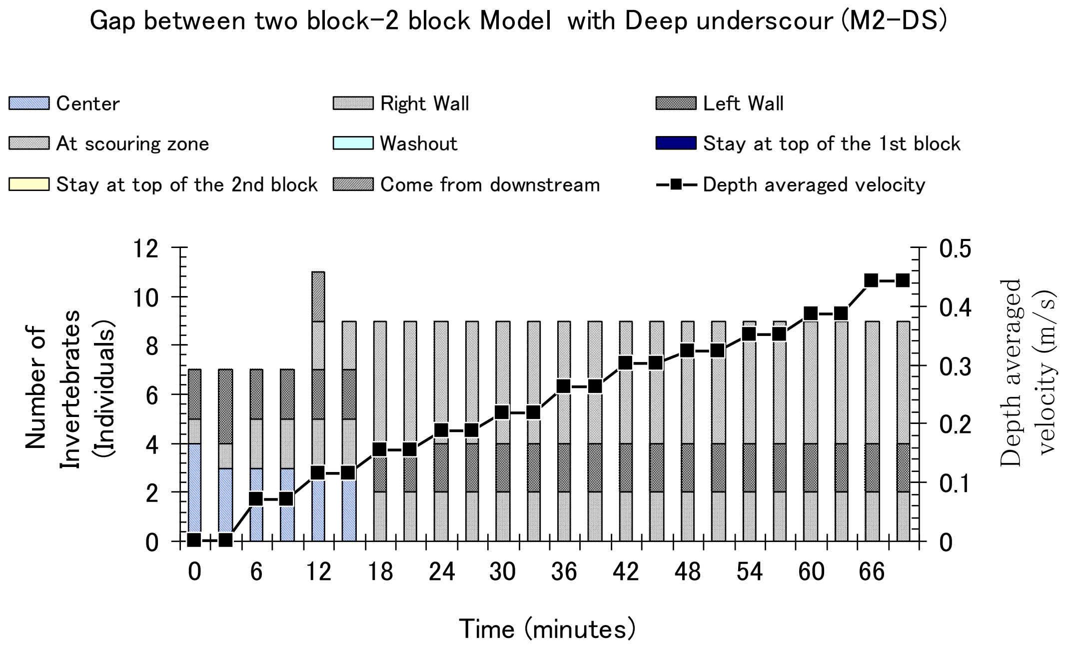

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Fig.4.4. Double block as refugia with Deep underscour (Case M2-DS) and their movement, position inside flume with time- observation (a) upstream of 1st block (Zone *U*) (b) downstream of 2nd block (Zone *D*) (c) in between 1st block and 2nd block (Zone *B*)); Left Wall refers to the invertebrates at left wall area (LWA), Right Wall refers to the invertebrates at right wall area (RWA), Center refers to the invertebrates at center area (CA); the number shows the total number of invertebrates in flume left wall, right wall and center.

It can be seen in Fig. 4.4 (c), inside the Zone *B*, most of the invertebrate position (i.e. numbers of invertebrates at left wall (LWA), right wall (RWA) and center (CA)) during low flows is different from invertebrate position during high flows. Active movement of invertebrates can be observed before depth averaged velocity (U_a) of 0.15m/s. After U_a of 0.15m/s, invertebrates don’t move and most of them are present inside the scouring zone (Zone *DS*) beneath the 1st block. The invertebrate numbers present in flume channel is more compared to shallow underscour case (Case M2-SS) at Zone *B*. This is due to underscour depth (D_s of 5mm) more than invertebrate body height (4mm). However, if we consider the stability of refugia (discussed in another section) then, deep underscour is not preferable (discussed in section 4.9).

4.5. Invertebrate response to change in hydraulic condition (velocity) for block as refugia-shallow underscour (Case M2-SS)

The invertebrates started to find refugia by walking, soon after the flow was introduced inside the flume (Fig.4.5). At Zone *U*, block’s front face as well as the side wall was used for refugia by invertebrates. At Zone *B*, the invertebrates preferred the central area (CA) than wall area (refer Fig. 2.2 for the definition of CA). Invertebrates actively walked for both Case A (uniform velocity stage) and Case B (velocity incremental stage).

At Zone *U* and Zone *B*, the active walking behavior was observed until the depth average velocity, U_a, of 0.35m/s (Fig. 4.5). For $U_a \geq 0.35$m/s, no walking behavior was observed. However, it was further observed that they could walk at any flow condition. This is because Zone *U* (upstream of Block1) and Zone *B* (gap between Block1 and Block2) provided good refugia. As a result, most of the invertebrates used active walking behavior for escaping out of the flume channel and most importantly no washout was observed for high flow conditions (Fig.4.6). However, the number of invertebrates remaining inside the Zone *B* was higher compared to Zone *U*.

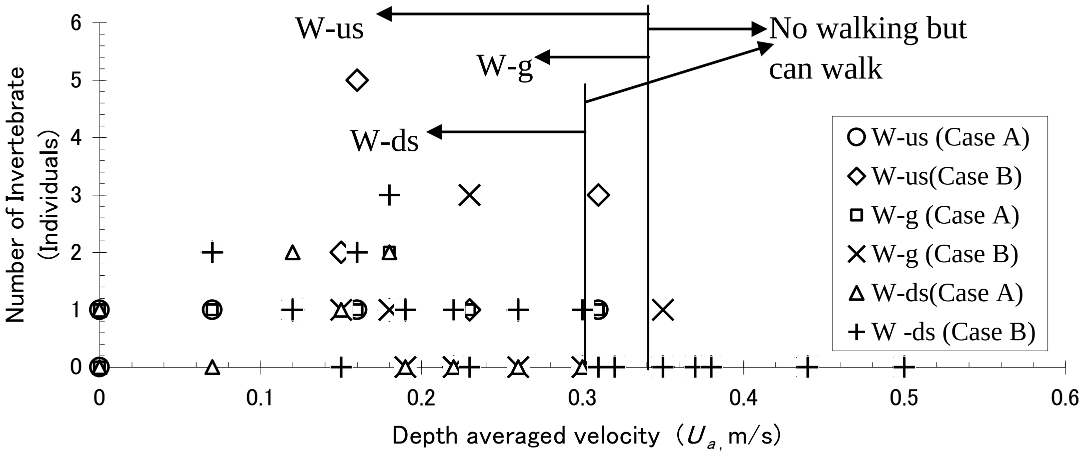


Fig.4.5. Critical value of depth average velocity for no walking in Zone *U* (W-us i.e. walking at upstream), Zone *B* (W-g i.e. walking inside gap) and Zone *D* (W-ds i.e. walking at downstream) – Case M2-SS; Case A-uniform flow velocity condition, Case B-incremental flow velocity condition

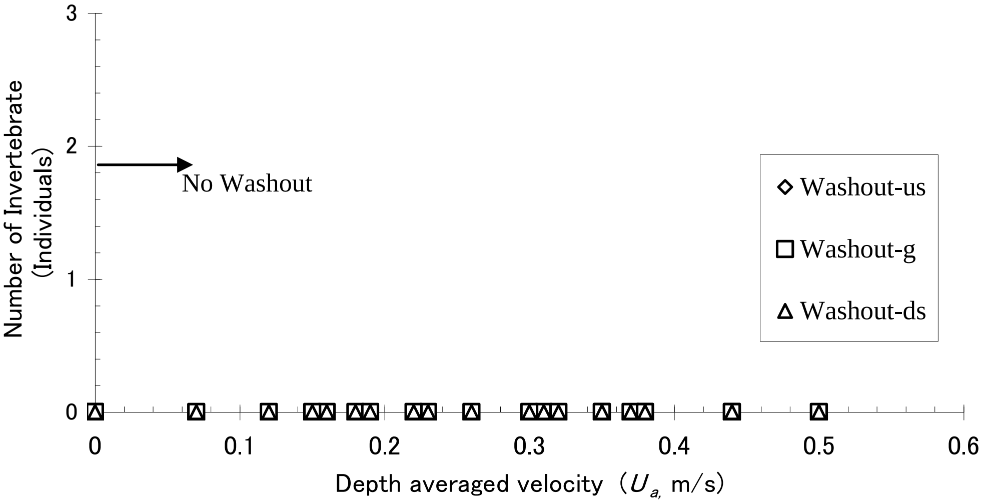


Fig.4.6. Critical value of depth-averaged velocity for washout in Zone *U* (upstream), Zone *B* (gap) and Zone *D* (downstream)-Case M2-SS; (Washout-us i.e. washout at upstream), (Washout-g i.e. washout inside gap), (Washout-ds i.e. washout at downstream); Case A-uniform flow velocity condition, Case B-incremental flow velocity condition

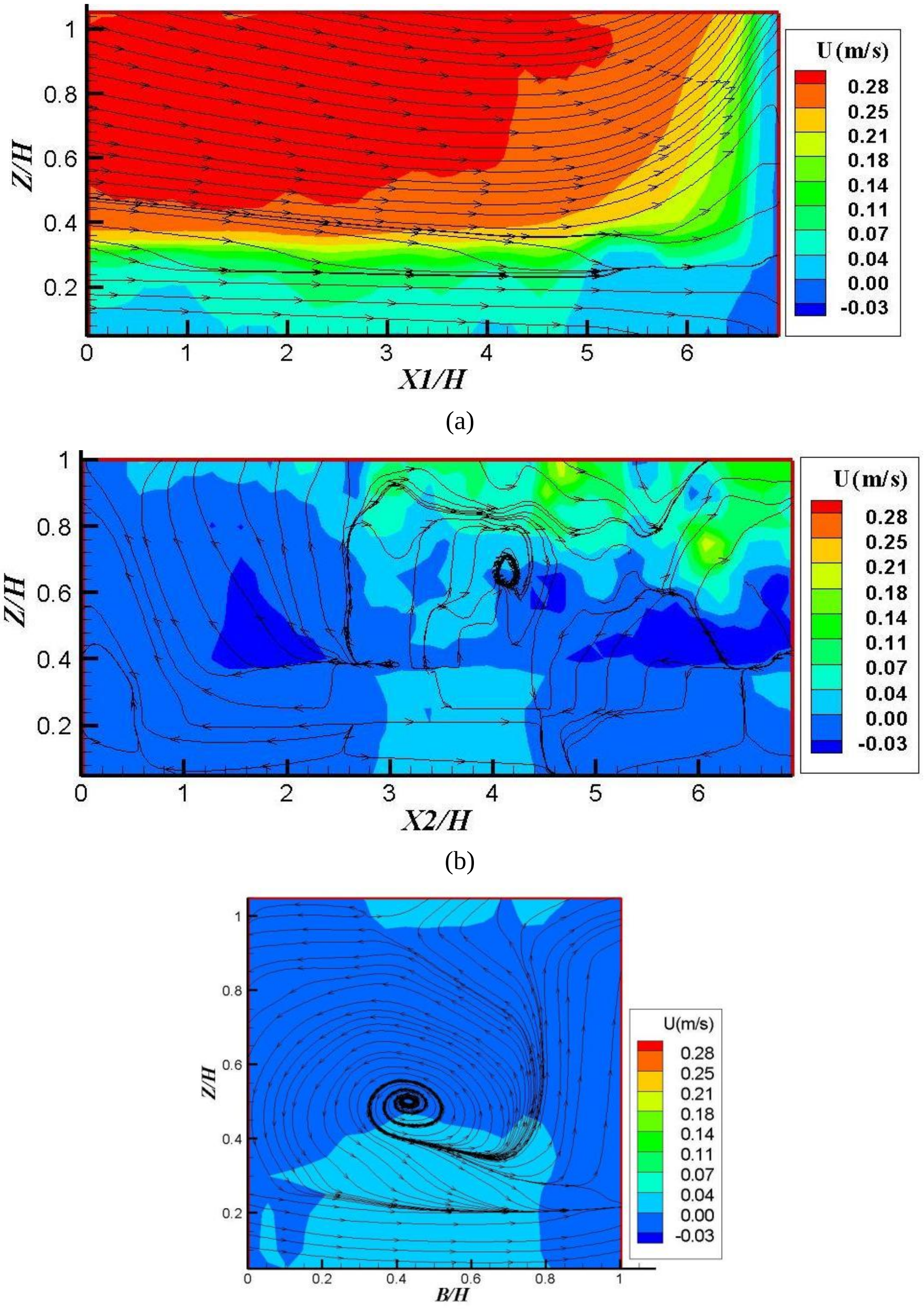


Fig. 4.7.Velocity and flow pattern (a) infront of Block1 as refugia (Zone *U*), (b) downstream of Block2 as refugia (Zone *D*), (c) in between Block1 and Block2 as refugia (Zone *B*) during high flow condition (7.4 cm water depth and 0.35m/s of depth average velocity); Invertebrate height is *Z/H* of 0.2. (See Fig. 2.20 for definition of Zone *D*, Zone *U* and Zone *B*)

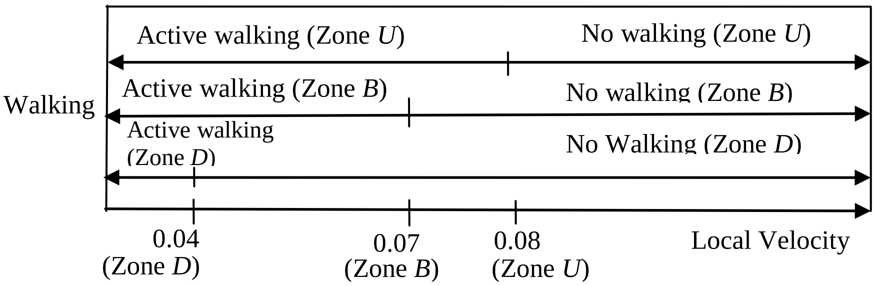


Fig.4.8. Summary for local velocity (m/s) around refugia (Case M2-SS) for a depth averaged velocity of 0.35m/s; Also, see Fig.4.7 (a), (b) and (c)

Fig. 4.7(a), 4.7(b) & 4.7(c) shows the velocity and flow pattern infront of Block1 as refugia (Zone *U*), downstream of Block2 as refugia (Zone *D*) and in between Block1 and Block2 as refugia (Zone *B*) respectively during high flow condition (7.4 cm water depth and 0.35m/s of depth averaged velocity).When refugia was introduced, the local velocity at the invertebrate height was always less than 0.10 m/s at Zone *U*, Zone *B* and Zone *D* even during high flow condition (Figs. 4.7 and 4.8). This value of local velocity with refugia is less than the no walking local critical velocity ($UCL_{no\ walking}$ of 0.12 m/s) without any refugia (Fig. 3.11). This is the reason why invertebrates don't get washed out or dislodged from their habitat during high flow conditions. This implies that refugia such as blocks can provide good shelter for invertebrates during flood conditions.

It can be seen Fig. 4.7(a), (b) and (c) that the velocity at the downstream of 2nd block (Zone *D*) is smaller at invertebrate height (Z/H=0.2) compared to upstream zone (Zone *U*) and gap (Zone *B*). However, Fig. 4.5 shows that critical depth average velocity for no walking is smaller than upstream zone (Zone *U*) and gap (Zone *B*). This could be due to higher turbulence at downstream zone (Zone *D*).

Bouckaert and Davis (1998) discussed about the benthic invertebrate's abundance in the wake than at the front boulders. However, in this study, it was also observed that the number of invertebrates remaining inside the Zone *B* was higher compared to Zone *U* and Zone *D*. One of the reasons could be the type of refugia used for the experiment. The blocks that we used in this experiment covers the whole width of the flume and flow from upstream overtops the blocks. So, the flow pattern would be different behind the refugia in this study than in the case of Bouckaert and Davis (1998). Moreover, the size of refugia used by Bouckaert and Davis (1998) was 55.8cm long, 48.5cm wide and 39.2cm tall. The height of the boulder above the water surface was 11.5cm. It means that the refugium was partially submerged. However, in this study, the size of refugia was smaller (8cm long, 25cm wide and 2cm tall) and fully submerged. So, it can be stated that the height of refugia to invertebrate height plays important role in providing refugia at downstream region. In this study the height of the refugia (*H*) to invertebrate height (H_I) is 5 whereas that of Bouckaert and Davis (1998) is 69.25. This is one of the reasons why in this study less invertebrates are present at downstream of block (Zone *D*).

Fig.4.7(b) shows the flow pattern behind the Block2. We can clearly see that for invertebrate height (Z/H =0.2), flow pattern at downstream of Block2 is not complex. Moreover, an eddy is seen above the invertebrate height. As for the upstream region (Zone *U*), where some underscouring occurs beneath the Block1, no eddy is seen. Invertebrate can escape out of the flume by walking from upstream zone because in this region also, local velocity around the invertebrate height (Z/H =0.2) is favorable for them to walk. In addition, swimming or drifting behavior was not observed at the upstream region. This can be explained by the fact that higher velocity exists from $Z/H \geq 0.4$ as shown in Fig. 4.7(a). We can see in Fig. 4.7(c) that inside Zone *B*, a large eddy is circulating in anti-clockwise direction just above the invertebrate height (Z/H =0.2). In natural condition, this kind of arrangement not only provides a low flow habitat zone but rich food availability zone. This study provides us the information about the invertebrate preference of refugia based on assemblage or movement behavior. However, the block as refugia needs to be investigated from stability point of view because if the refugium is not stable then it cannot provide refugia.

4.6. Flow pattern between shallow and deep underscour depth and effect of D_s/H (underscour depth) and B/H (horizontal spacing between two blocks as refugia) on flow pattern at Zone *B*

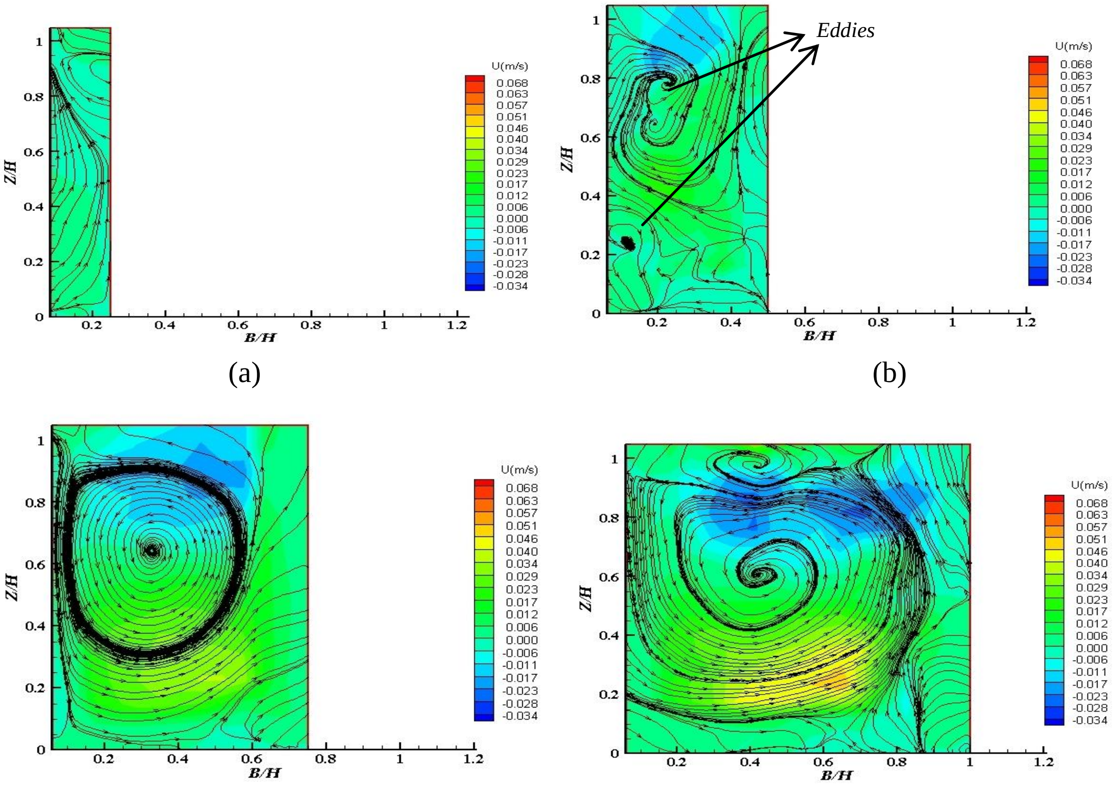
This section discuss and compares the flow pattern between shallow and deep under scour depth and the effects of spacing between two blocks (refugia) on flow pattern inside Zone *B*. Fig. 4.9 (a), (b), (c) and (d) shows the streamline pattern in Zone *B* with non-dimensional horizontal gaps (B/H) of 0.25, 0.50, 0.75,1 respectively for a constant non-dimensional scour depth (D_s/H) of 0.05. For flow pattern in Zone *B*, with underscour depth (D_s/H) of 0.10, 0.15 and 0.20, see APPENDIX 5. Fig. 4.9(a) shows that a large eddy pattern was not created when B/H is 0.25, and the velocity inside Zone *B* was not much changed. When *B/H* was increased to 0.5, two small eddies were created (Fig. 4.9(b)). One was near the bottom, and the other was above. Moreover, Fig. 4.9(c) and 4.9(d) shows a large eddy with a distinct shape. The explanation for this is that even though the D_s/H was small, the wider *B/H* allowed the free passage of water between them. As a result, the velocity was increased with increasing *B*/*H*, and a large velocity difference was created between the first block's rear wall and the central portion of the gap. Thus, a wider *B/H* generated a larger eddy.

Fig. 4.10 (a),(b),(c) and (d) shows the streamlined pattern in Zone B with non-dimensional horizontal gaps, *B*/*H* ,of 0.25,0.50,0.75,1 respectively and the largest D_s/H (0.25) in the experiment. Similar to Fig.4.9 (a), the flow in Zone *B* was almost stagnant when *B*/*H* was 0.25. Even when deep underscouring occurred, the flow pattern in Zone *B* was not much altered in comparison with the case of shallow underscouring. When *B*/*H* was larger than 0.5, a very small eddy was formed near the rear wall of first block. In this case, unlike the small underscouring with the same horizontal spacing where two eddies were formed, a single eddy was formed near the Zone B exit. When *B*/*H* was further increased to 0.75, the eddy was large but not as large as with the shallower underscour (D_s/H=0.05 and *B/H*=0.75). When the horizontal gap was further increased to a *B*/*H* of 1.0, a large eddy was formed, but it was not as strong as in earlier cases (D_s/H of 0.05, 0.10, 0.15, and 0.20 with the same *B*/*H* (=1.0)). By comparing Fig. 4.10 (d) with Fig.4.9 (d), it can be seen that eddy formation was weaker for deeper underscours. This is because, for the same horizontal spacing, more flux came from Zone *DS* to Zone *B* when underscour depths (D_s/H) were deeper (Table 4-1).

Table 4-1 Unit discharge influx (m^2/s) to Zone *B*

D_s/H	*B/H*			
	0.25	0.50	0.75	1.00
0.05	0.00030	0.00050	0.00061	0.00269
0.10	0.00039	0.00051	0.00074	0.00336
0.20	0.00091	0.00100	0.00127	0.00525
0.25	0.00160	0.00190	0.00300	0.00771

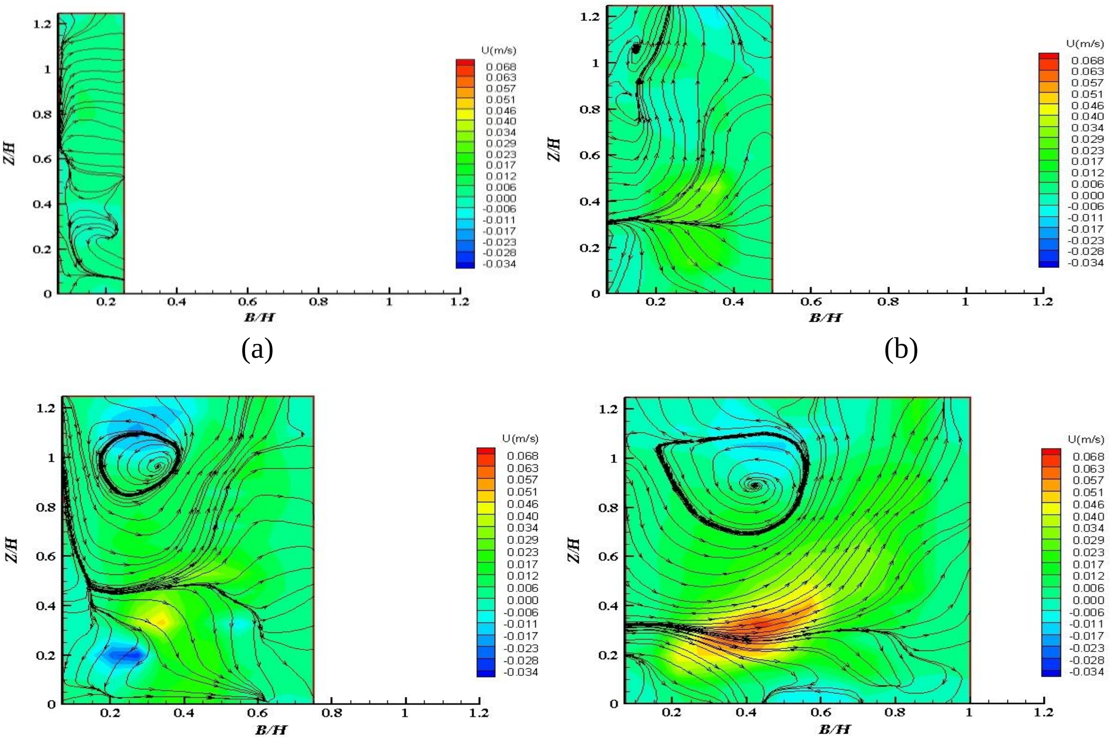
As a result, the velocity difference between the region of the first block's rear face and the central region of Zone B became smaller with increasing D_s/H.



(a) (b)

(c) (d)

Fig.4.9. Flow pattern in Zone *B* when non-dimensional underscour depth D_s/H is 0.05 and (a) *B/H*=0.25, (b) *B/H*=0.5, (c) *B/H*=0.75, and (d) *B/H* =1.0



(a) (b)

(c) (d)

Fig.4.10. Flow pattern in Zone *B* when non-dimensional underscour depth D_s/H is 0.25 and (a) *B/H*=0.25, (b) *B/H*=0.5, (c) *B/H*=0.75, and (d) *B/H* =1.0

The flow pattern obtained from this study can be compared with the flow pattern over boulders or cobbles forming step pools. Chanson (2001) determined that nappe flow occurs on boulder sills when $d_c/H < 1$, where d_c is the critical flow depth and H is the drop height, while transition flow develops when $0.85 \leq d_c/H \leq 1.15$, approximately. If $d_c/H > 1$, skimming flow develops, in which the water flows over the step pool in a coherent stream with recirculation in the pools beneath. In our study, $d_c/H \approx 2$, so a similar skimming flow pattern was observed with recirculation in Zone B. However, in this study, the flow pattern, eddy size, and eddy location were affected by underscour depth and horizontal spacing between two blocks.

4.7. Effects of D_s/H and B/H on pressure and its distribution around the block (refugia)

The pressure distribution around the first block (scoured block) and the effect of D_s/H and B/H is discussed in this section. Table 4-2 shows the pressure distribution on the top surface, bottom surface, front face, and rear face of the first block when B/H was varied from 0.25, 0.50, and 0.75, to 1 with the same D_s/H of 0.05. The B/H did not much alter the pressure distribution trend around the block. For all B/H and D_s/H of 0.05, pressure gradually decreased on the top surface of the first block from the leading to trailing edges. The pressure distribution on the top surface of a sharp-edged object has been reported in previous research. Taylor et al. (2010) showed that on the top surface, the separation of flow occurs near the sharp edge (leading edge) and the flow reattaches at some distance from the leading edge. This is the reason for the higher pressure near the leading edge. Shortly after the flow reattachment, the velocity increases and pressure gradually decreases from halfway to trailing edge. The pressure distribution on the bottom surface is mostly affected by the horizontal space between the two blocks. If there were no gap between the two blocks, then the pressure distribution at the bottom surface would be uniform. However, due to the presence of horizontal spacing, the pressure on the bottom surface varies. For all B/H and D_s/H of 0.05, on the bottom surface of the first block, the pressure was high on the left side (entrance of Zone *DS*) and low on the right side (exit of Zone *DS*).

On the front face, the pressure distribution rose from low to high from top to bottom. This can be explained by the fact that little fluid can pass through the shallow underscour. As a result, the flow was slightly stagnant in front of the block even though scouring exists. At the same time, some flow will move towards the leading edge from the bottom stagnant area. Thus, high velocity and low pressure was seen at the top of the front face, while low velocity and high pressure were seen at the bottom of the front face. The pressure distribution trend at the rear face of the first block was such that the pressure was high at the top (just below the trailing edge) and low at the bottom (above the exit of Zone *DS*). This can be seen in Fig. 4.9(a)-(d), which shows that there was less flow at the top rear face than at the bottom rear face. Although some flow entered from the top surface to Zone *B*, the mixing of flow at Zone *B* occurred far from the trailing edge. Thus, the flow near the top rear face was stagnant and the pressure was higher. However, due to the presence of the underscour region (Zone *DS*), the flow was always active near the bottom rear face, and the pressure was consequently lower at the bottom rear face.

Table 4-2 Distribution of pressure (in kg/cm^2 x 10^{-3}) measured at top surface, bottom surface, front face, and rear face of first block for a non-dimensional under-scour depth (D_s/H) of 0.05

Measured sides	*B/H*											
	0.25			0.50			0.75			1.00		
	FP	MP	LP	FP	MP	LP	FP	MP	LP	FP	MP	LP
Top surface	7.48	7.21	6.28	7.65	6.85	6.41	7.64	6.86	6.48	7.71	6.86	6.44
Bottom surface	7.53	7.31	7.15	7.35	7.23	7.05	7.46	7.09	6.90	7.43	6.97	6.88
	TP	BP		TP	BP		TP	BP		TP	BP	
Front face	8.04	8.48		8.03	8.48		8.05	8.42		8.12	8.38	
Rear face	7.09	6.72		7.09	6.74		7.14	6.70		7.17	6.80	

Note: FP=First Point, MP=Middle Point, LP=Last Point, TP=Top Point, BP= Bottom Point; (For definition see Fig. 2.24)

Table 4-3 Distribution of pressure (in kg/cm^2 x 10^{-3}) measured at top and bottom surfaces and front and rear faces of first block with a non-dimensional under-scour gap (D_s/H) of 0.25

Measured sides	*B/H*											
	0.25			0.50			0.75			1.00		
	FP	MP	LP	FP	MP	LP	FP	MP	LP	FP	MP	LP
Top surface	8.04	7.77	7.28	7.99	7.81	7.38	7.82	7.72	7.27	7.44	7.36	7.22
Bottom surface	9.09	8.84	8.00	8.67	8.20	8.01	8.22	7.99	7.98	7.68	7.68	7.69
	TP	BP		TP	BP		TP	BP		TP	BP	
Front face	7.98	8.66		7.99	8.63		7.98	8.56		7.94	8.47	
Rear face	7.23	6.83		7.54	6.81		7.59	7.04		7.61	7.11	

Note: FP=First Point, MP=Middle Point, LP=Last Point, TP=Top Point, BP= Bottom Point; (For definition see Fig. 2.24)

Table 4-3 shows the pressure distributions at the top surface, bottom surface, front face, and rear face of the first block when *B/H* was varied from 0.25, 0.50, and 0.75, to 1 with the same D_s/H of 0.25. For all *B/H* values, the pressure distribution trend was similar to that of D_s/H of 0.05 at the top surface, rear face, and front face. However, at the bottom surface, the pressure distribution trend was high to low from left to right when *B/H* was 0.25, and the pressure was uniformly distributed when *B/H* was 1.

The effects of D_s/H and *B/H* are much clearer in Table 4-3. First, more flow entered Zone *DS* with increasing underscour depth. However, the amount of flow that exited from Zone *B* was not much changed from the case of a small underscouring depth for the same *B/H*. Hence, the flow was more stagnant with deep underscouring, and high pressure occurred at the first block’s rear and bottom surfaces. Secondly, when underscouring was deep, a large horizontal spacing (*B/H*) was more effective for the stability of the first block. This is because high pressures were generated at the front and bottom surfaces for the initial horizontal spacing (*B/H*) of 0.25. As the horizontal spacing increased, the pressure on the block’s bottom surface gradually decreased while the pressure at the block’s rear face increased. The pressure at the bottom surface was reduced in such a way that the pressure distribution was uniform for a *B/H* of 1.00 (Table 4-3). This demonstrates that for deep underscouring, blocks are more stable if wider gaps are kept between the two blocks.

4.8. Drag and Lift coefficient

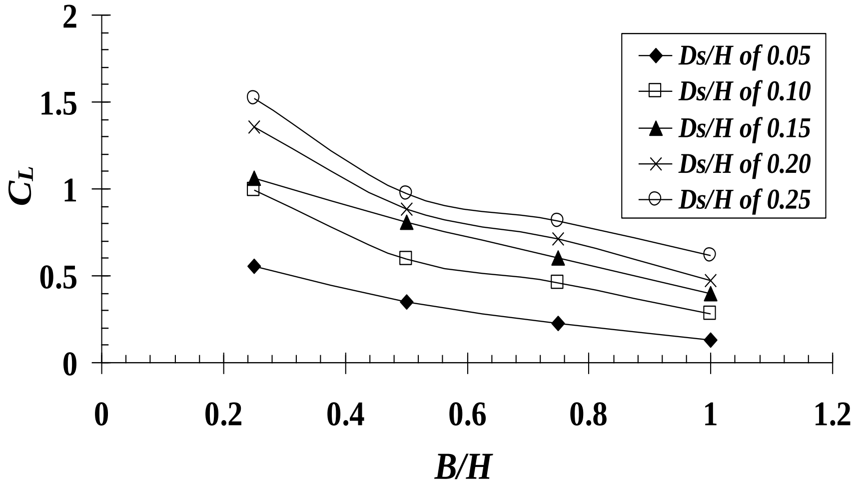


Fig.4.11. Lift coefficient (C_L) trend for different non-dimensional horizontal spacings (*B/H*) and non-dimensional underscour depths (D_s/H) of front block; (See equation 1, section 2.7.2 for definition of C_L)

Fig. 4.12 shows the relationship between *B*/*H* and lift coefficient with different D_s/H. For the same D_s/H, the lift coefficient decreased with increasing *B*/*H*. This is because more flux came into Zone *B* with increasing *B*/*H* (Table 4-1), and the flow easily passed through Zone B. As a result, the flow was not stagnant in Zone *B* and Zone *DS*. In addition, the pressure acting at the top surface was less than on the bottom surface of the block (Table 4-4). Furthermore, the horizontal gap between the two blocks did not affect the pressures on the top surface of the first block and they were not altered much, but the pressure at bottom surface was decreased as the size of the horizontal gap increased (Table 4-4). Hence, the pressure differences between the top and bottom surfaces of the first block decreased with increasing B/H. Therefore, the lift coefficient decreased with increasing B/H. For the same B/H, the lift coefficient increased when D_s/H increased. In this condition, the eddy was more dominant than the flux coming into Zone *B*. The flow patterns shown in Figs. 4.9(c) and 4.10(c) show that the velocities at the rear face of the first block became slower when D_s/H increased, and thus the shear force acting downward at the rear face of the first block became smaller and as a result the lift coefficient increased when D_s/H increased.

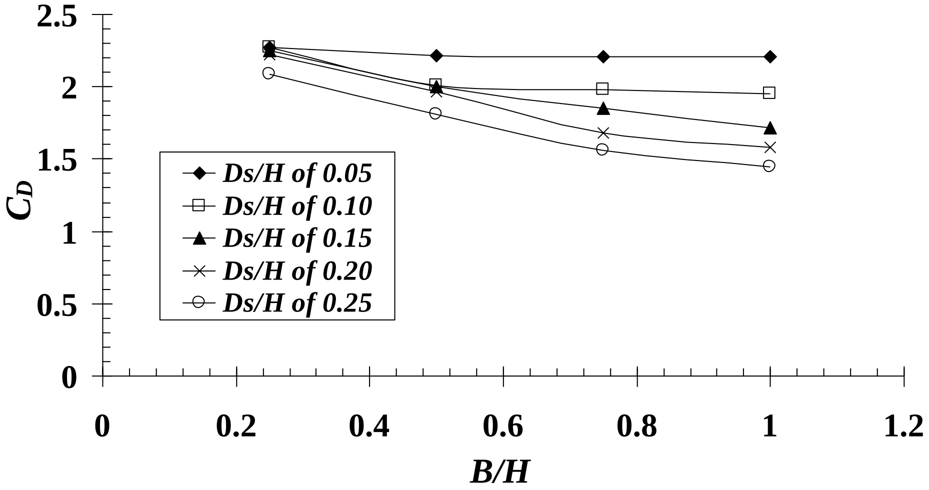


Fig.4.12. Drag coefficient (C_D) trend for different non-dimensional horizontal spacings (B/H) and non-dimensional underscour depths (D_s/H) of front block; (See equation 2, section 2.7.2 for definition of C_D)

Fig. 4.12 shows changes in the relationship between B/H and drag coefficient (C_D) with different D_s/H. For the small D_s/H of 0.05, the drag coefficient was the highest, but its value was almost the same regardless of B/H. However, for D_s/H of 0.1 or greater, the drag coefficient was decreased with increasing B/H for the same underscour depth. This can be explained by the fact that the pressure at the front face was greater than at the rear face of the block, and when B/H values were increased, the pressure acting at the first block's front face was almost constant, but the pressure acting on the rear face increased (Table 4-

4). Thus, the pressure difference between the front and rear faces of the first block became smaller with increasing B/H, and the drag coefficient became smaller. Moreover, for the same B/H, the drag coefficient decreased when D_s/H increased. The reason is that the pressure at the front face was not changed much, but the pressure at the rear face increased (Table 4-4). The pressure difference between the front and rear faces of the first block became smaller for larger D_s/H. Therefore, for the same B/H, drag coefficient decreased with an increase in D_s/H.

Table 4-4 Pressure (in kg/cm^2 x 10^{-2}) around the first block for a non-dimensional under-scour depth (D_s/H) of 0.05 and 0.25

D_s/H	Measured sides	B/H			
		0.25	0.50	0.75	1.00
0.5	Top surface	2.10	2.10	2.10	2.10
	Bottom surface	2.20	2.16	2.14	2.13
	Front face	1.70	1.70	1.70	1.70
	Rear face	1.38	1.39	1.39	1.40
0.25	Top surface	2.30	2.30	2.30	2.20
	Bottom surface	2.60	2.50	2.40	2.30
	Front face	1.70	1.70	1.70	1.70
	Rear face	1.40	1.43	1.47	1.48

This result contrasts with the result obtained by Shah et al.,(2010), who investigated the drag coefficient and lift coefficient of a single block with underscouring (D_s/H=0.25) and without underscouring (D_s/H =0). Their results show that when D_s/H changed from 0 to 0.25, the drag coefficient increased from 0.57 to 0.66, respectively, and the lift coefficient decreased from 0.70 to 0.58, respectively.

The drag coefficient for submerged large woody debris (LWD) can be compared to the drag coefficient for bed protection blocks because both obstruct the flow. As in the case of flow in open channels, as suggested by Wallerstein et al. (2001), the drag coefficient is a function of the LWD element geometry (shape and orientation), submergence ratio (z/d: where z is the depth from the water surface to the center of LWD and d is the diameter of LWD), Froude number (Fr: based on approach velocity and diameter of LWD), and Reynolds number. However, for intermediate to very large Reynolds numbers (1,000–30,000) and submergence ratios (z/d) ≥ 8, the drag coefficient depends only on LWD element geometry. Wallerstein et al. (2001) noticed that at $z/d < 8$, C_d varied considerably with submergence ratio and Froude number. They found that the drag coefficient increased with decreasing submergence ratio and that the drag coefficient reached a maximum at Fr =0.50.

This experiment did not consider different submergence ratios and Froude numbers because the objective was to analyze the drag and lift coefficients for different underscour depths and horizontal distances between two bed protection blocks. However, if the values of the submergence ratio, Froude number, and slenderness ratio (d_b/L), where d_b is the height of the block and L is the width of block, are calculated using this study, then z/d_b=3.5, Fr=0.45, and d_b/L=0.04. For these values, the drag coefficient obtained from this study was greater than that (C_d =0.715) obtained by Wallerstein et al. (2001). Shah et al., (2010) obtained similar C_d values for the case of a single block, and this study would have obtained a similar drag coefficient if there had been only a single bed protection block. The larger drag coefficient was due to the presence of two bed protection blocks and the space between them.

Hygelund and Manga (2003) showed that C_d varied with depth ratio for a single wooden log lying perpendicular to the flow at a certain height from bed surface. The depth ratio was defined as the height of the water below the wooden log (b) divided by the sum of the distances above and below the wooden log ($a+b$). Their results show that C_d increased by 2.5 times when depth ratio increased from 0.2 to 1.0. The C_d increased by this amount only for wooden log diameters less than or equal to one-third of the channel water depth. In this study, the block height was less than 1/3 of the channel water depth and the underscour depth was comparable to the height of the water below the wooden log (b). In this case, in contrast to the results obtained by Hygelund and Manga (2003), the drag coefficient decreased with increased depth ratio. This was due to presence of another block behind it.

Hygelund and Manga (2003) also noted that when wooden logs are placed near the bottom, the C_d did not seem to increase in their measurements. In contrast, this study results showed an increase in the drag coefficient when underscour depths were smaller for the same horizontal spacing between two blocks, which is due to the stagnant water region created upstream and downstream of the block by the shallow underscour depth compared to a deep underscour depth.

4.9. Stability of blocks

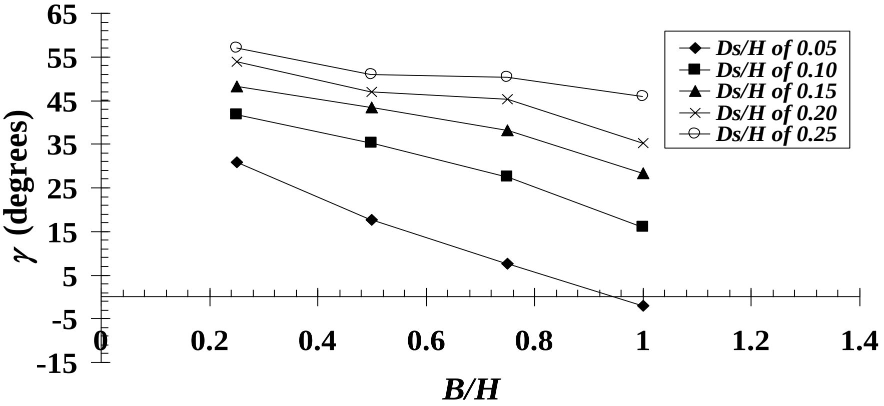


Fig.4.13. Stability at different non-dimensional horizontal spacings (*B/H*) and non-dimensional underscour gaps (D_s/H) of a block

Fig. 4.13 shows the relationship of γ (angle made by resultant force and critical diagonal line) to *B/H* (horizontal spacing between two blocks) and D_s/H (underscour depth). It can be concluded that the block is stable only for D_s/H of 0.05 with *B/H* of 0.9–1. For all other cases, a block will collapse in these flow conditions. However, blocks are more stable with a shallow underscour depth than the deep underscour depth. It is hard to prevent the collapse of the block when two blocks have small spacing between them and a deep underscour. Therefore, for stability, a horizontal distance of *B*=*H* should be maintained between two blocks, especially at the front side of the block-protected region where the scouring can easily occur. Wallerstein et al. (2001) have reported that flow obstructing objects such as LWD can become (relative to a constant discharge) more stable (relative to displacement) at a given location in a channel through time because the drag force generated by a given flow acting on LWD may decrease with time, due to erosion of the channel boundary. In this study, if it were to be assumed that underscour depth increases with time, then Fig. 4.12 shows that the drag coefficient decreased with increasing underscouring depth. This result, although obtained using multiple blocks (it assumed multiple flow-obstructing objects), is similar to that of Wallerstein et al. (2001) (a single flow-obstructing object). However, their results do not account for the fact that the stability of the flow obstructing objects (LWD) was affected by both drag force and lift force. Thus, result from this study shows that blocks were less stable through time (at deep underscour depth) due to the combined effect of drag and lift forces acting on them (Fig. 4.13).

CHAPTER 5

CONCLUSION AND FUTURE RECOMMENDATIONS

5.1. Conclusion in each chapter

This study was conducted to determine the invertebrate response to approach flow velocity without roughness(smooth bed), invertebrate response to approach flow velocity with roughness (rough bed), providing block as refugia for invertebrates, water flow pattern between two neighboring blocks (refugia), to elucidate the pressure distribution around the scoured block (refugia), and to investigate the optimal spacing between two neighboring blocks (refugia) when underscouring of first block (refugia) occurs. The following conclusions can be made from this study.

This experiment shows that an invertebrate behavior can be categorized based on the approach flow velocity without any refugia and roughness. They are active walking, no walking, and washout behavior. Invertebrates showed active walking behavior, for a depth averaged velocity less than 0.2m/s, no walking behavior for a depth averaged velocity of 0.2-0.4m/s and washout behavior for depth average velocity more than 0.4m/s. Invertebrate also showed endurance behavior from depth averaged velocity value of less than 0.4m/s.The critical depth averaged velocity for no walking is 0.2 m/s and washout is 0.40m/s. Without roughness (smooth bed), the critical local velocity around the invertebrate height for no walking is 0.12 m/s and washout is 0.22 m/s.

This experimental study shows the effect of turbulence generated by upstream gravel roughness in a flume channel on invertebrate behavior such as no walking and washout. With the roughness (WR), critical depth averaged velocity for no walking is increased from 0.2m/s (WOR) to 0.3m/s but critical depth averaged velocity for washout is decreased from 0.4m/s (without roughness (WOR) case) to 0.33m/s. The depth averaged velocity cannot estimate well the invertebrate behavior. Instead, local velocity at invertebrate height (4mm from bottom bed), the local critical velocity for no walking without roughness (0.12m/s) is similar to the value without roughness (0.1 m/s). For washout, the local critical velocity value without roughness (0.22 m/s) is decreased when the roughness is introduced (0.12 m/s). So, the local velocity is found to be more important than depth averaged velocity for understanding invertebrate behaviors. Moreover, if depth averaged velocity is considered for invertebrate behavior analysis, then, SC_S which is shear component of turbulent intensity is responsible for invertebrate behavior such as no walking and washout. However, if local velocity is used for behavioral analysis then, with the introduction of roughness, at invertebrate height level, we can conclude that local turbulent intensity, SC_L which is related to drag force that act along their body is responsible for invertebrate's no walking behavior, whereas local turbulent intensity, VC_L which is responsible for lifting invertebrate is more responsible washout of invertebrates. So, this study shows that the need for refugia is more under the turbulent condition of flow. Although this study doesn't accurately predict the drift distance after dislodgement due to flume size limitation but the study shows that dislodgement of invertebrate is not increased with flow and the shear stress required to dislodge an invertebrate such as I*sonychia japonica* on a immoveable bed is higher without roughness (3.41 N/m^2) than with roughness (0.12 N/m^2)

Different types of refugia were provided for invertebrates. Wooden blocks were used as refugia in the flume experiment. The two block setup with spacing (*B*) equal to height of the block (*H*) with small underscour and deep underscour at frontal block showed good results based on number of invertebrate remain inside the flume. When refugia were provided, the invertebrates were able to walk for depth averaged velocity of 0.35 m/s i.e. is 40% increase in flow condition. With refugia, active walking and no walking behavior were observed but washout behavior was not observed. With the introduction of refugia, the local velocity around the invertebrate height was reduced to less than 0.10m/s for high flow conditions.

Suitable refugium was provided for the invertebrate. Flow pattern between two neighboring blocks (refugia) with an underscour below frontal block, the pressure distribution around the scoured block (refugia), the optimal spacing between two neighboring blocks (refugia) when underscouring of frontal block (refugia) occurs were analyzed. The stability of refugia was investigated.

The flow pattern between two neighboring blocks was different for different horizontal spacings and underscour depths. It was noted that an eddy was not generated with small horizontal gaps between two neighboring blocks and that larger eddies were generated with wider gaps. Further, when underscouring was deep, eddies were generated but were small in size compared to eddies generated when the underscour was shallow.

The effect of wider horizontal gaps can be assumed to be significant in reducing the pressure on the bottom surface of a scouring block. For small and large underscours with a small horizontal space (*B/H*), the pressure distribution at the bottom surface decreases from front to back. However, for a deep underscour and a wide horizontal space (*B/H*=1), the pressure distribution was almost uniform at the bottom surface. Moreover, when the size of horizontal gaps was increased, the pressure acting on the top surface and front face was not altered much, while the pressure on the bottom surface was decreased and pressure on the rear face was increased.

The drag and lift characteristics also explain the importance of wider spacing between two neighboring blocks during underscouring of the frontal block. Under the same underscour conditions, the lift and drag coefficient decreased when the horizontal gap between two blocks increased. Moreover, with the same horizontal gap between two blocks, the lift coefficient increased and drag coefficient decreased with increasing underscouring depth. The results demonstrate that wider horizontal spacing between two blocks is effective to prevent or reduce the possibility of collapse of the front block when the underscouring becomes deeper.

With shallow underscouring depths, the bed protection blocks seemed to achieve stability when gaps between two bed protection blocks (*B*) were equal to height of the block (*H*).

5.2. Overall conclusion

The results in this study provide fundamental information about invertebrate behavior based on response to approach flow velocity. From this study, without any refugia and under smooth bed condition, invertebrate behavior has been categorized as active walking behavior for a depth averaged velocity less than 0.20m/s, no walking behavior for a depth averaged velocity between 0.20-0.40 m/s and washout for a depth averaged velocity more than 0.40 m/s. Invertebrates also show enduring behavior. Although, the level of endurance couldn’t be measured, it is assumed that level of endurance is small during low flow condition and large during high flow condition. This behavior categorization according to approach flow can be applied for other invertebrates which have similar behaviors. The effect of turbulence generated by artificial roughness using gravel of 4mm diameter had significant effect on their movement behavior in relation to approach flow velocity. With the introduction of roughness, the critical depth averaged velocity is altered to 0.3m/s and 0.33m/s for no walking and washout behavior respectively. Moreover, the depth averaged velocity cannot estimate well the invertebrate behavior and local velocity should be used to analyze the invertebrate behavior. Without roughness, the local velocity for no walking and washout is 0.12m/s and 0.22m/s respectively whereas with roughness its 0.10m/s and 0.12m/s respectively. The effect of turbulence is such that if we consider depth averaged velocity and spatial turbulent intensity, then shear component of turbulent intensity is responsible for invertebrate behavior such as no walking and washout. But if we consider local velocity and local turbulent intensity then shear component which is related to drag force that act along their body is responsible for invertebrate’s no walking behavior, whereas vertical component which is responsible for lifting invertebrate is more responsible washout of invertebrates. In future, invertebrate needs to be investigated for higher turbulence than turbulence used in this study. A refugia setup of two wooden blocks was successful in providing refugia in this study. The hydraulic analysis shows that local velocity was reduced to 0.10m/s at invertebrate height due to the presence of block as refugia. Similar block arrangement (with horizontal spacing equal to height of the block) has a possibility to provide refugia in a stream. This study also provides fundamental information about flow patterns around a block (refugia), drag and lifts coefficients, and the effect of horizontal spacing between two blocks (refugia) on reducing drag and lift forces acting on them. Moreover, the stability of refugia can be strengthened by making horizontal spacing between two blocks (refugia) equal to height of block (refugia). In future, additional experiments can also be done to investigate the effects of Froude number and block (refugia) geometry on lift and drag coefficients of the block (refugia) which ultimately affect the invertebrate movement behavior, its habitat suitability around refugia and the stability of refugia.

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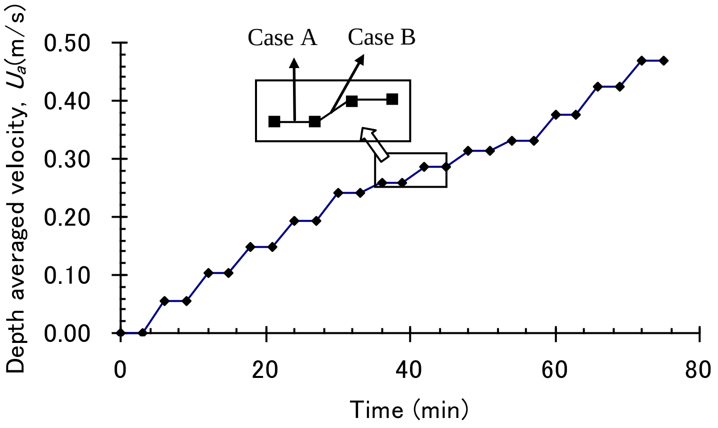
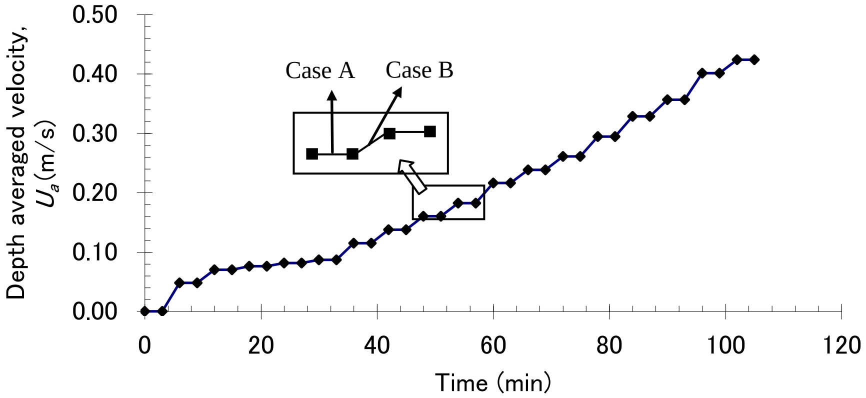
APPENDIX

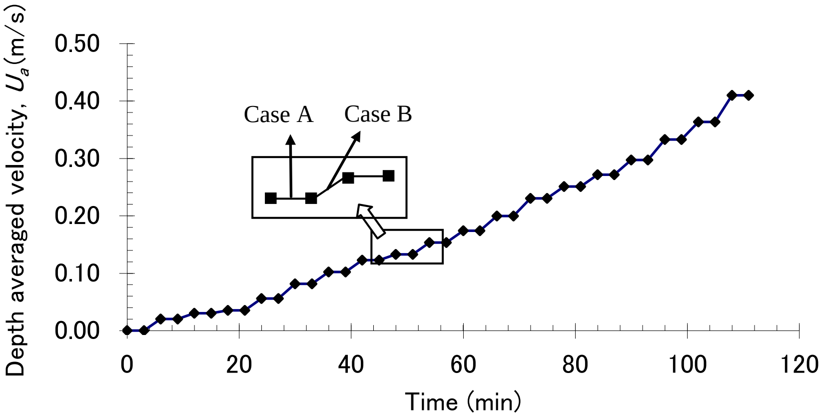
APPENDIX 1: Velocity increment with time for with roughness (WR), without single block (M1), without double block (M2), double block with shallow underscouring (M2-SS), double block with deep underscouring (M2-DS)



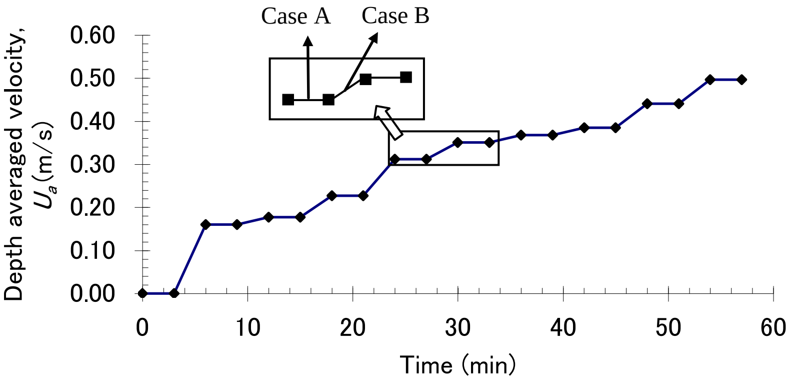
A1-1. Velocity increment with time (with roughness –WR); Case A represents uniform flow stage and Case B represents incremental flow stage



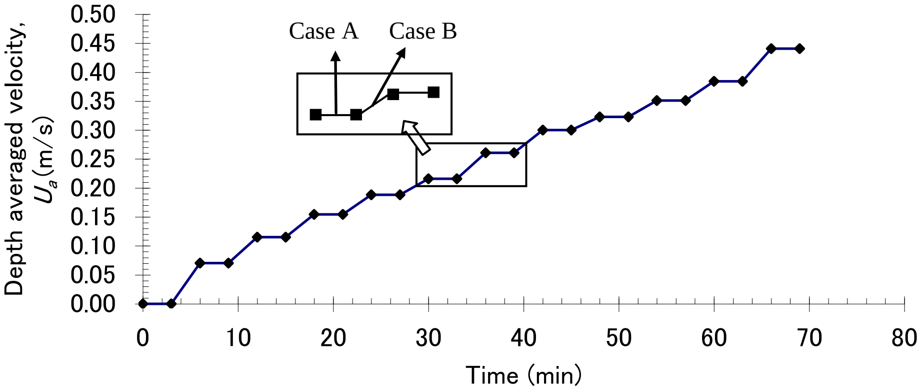
A1-2. Velocity increment with time (without single block –M1); Case A represents uniform flow stage and Case B represents incremental flow stage



A1-3. Velocity increment with time (without double block –M2); Case A represents uniform flow stage and Case B represents incremental flow stage

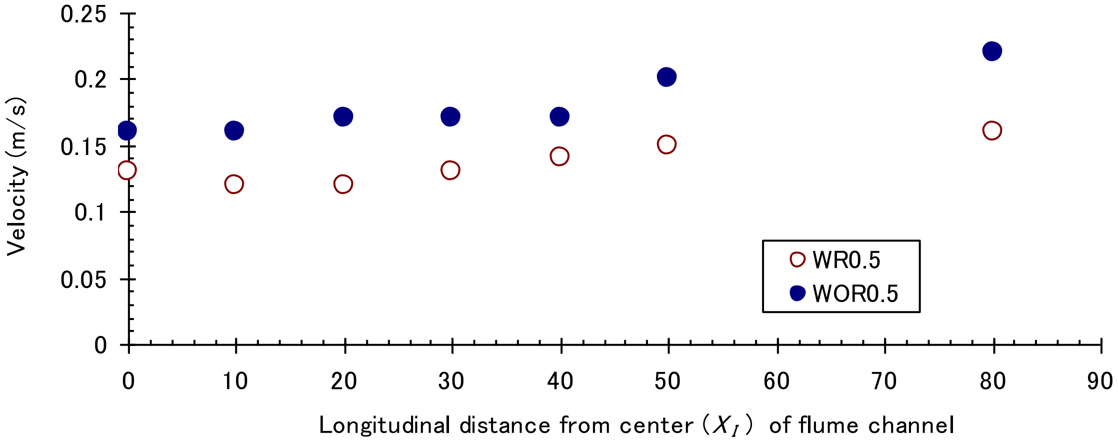


A1-4. Velocity increment with time (double block with shallow underscouring – (M2-SS)); Case A represents uniform flow stage and Case B represents incremental flow stage

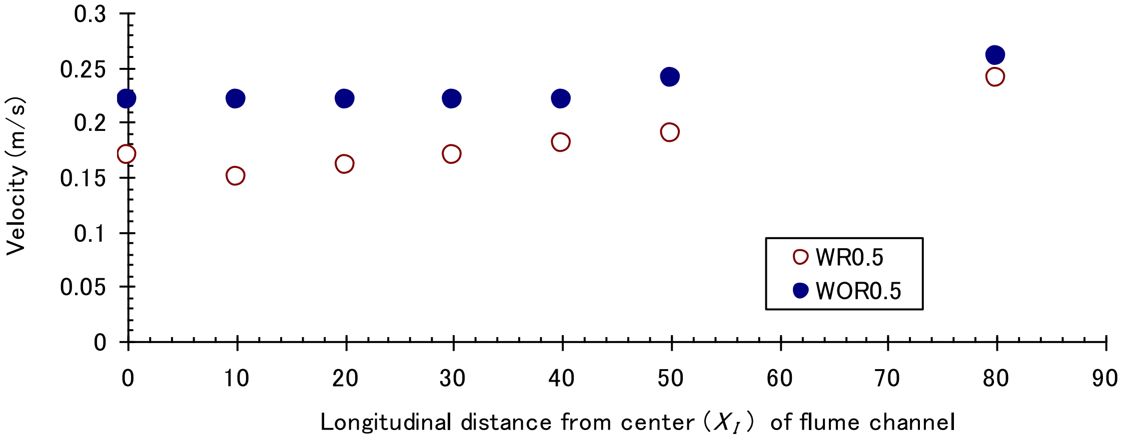


A1-5. Velocity increment with time (double block with deep underscouring – (M2-DS)); Case A represents uniform flow stage and Case B represents incremental flow stage

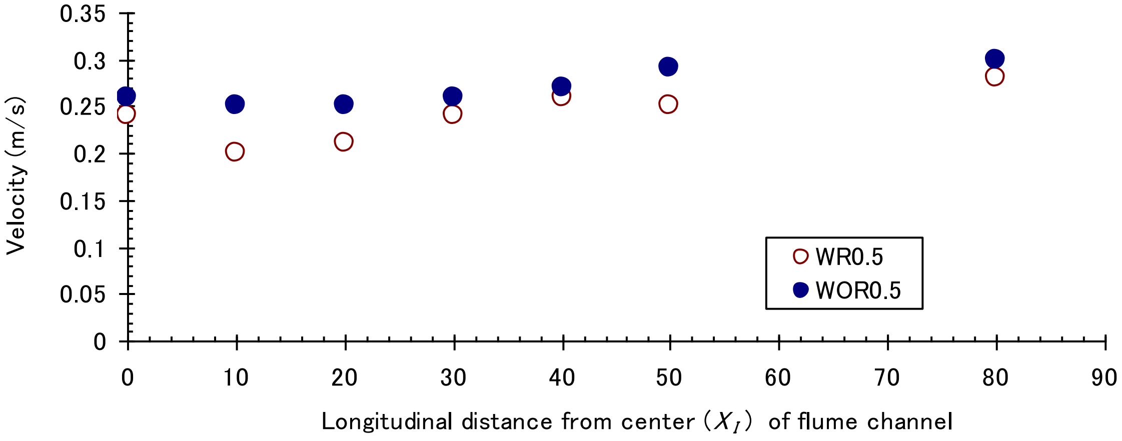
APPENDIX 2: Longitudinal velocity profile in the flume (from electromagnetic velocity meter)



(a)

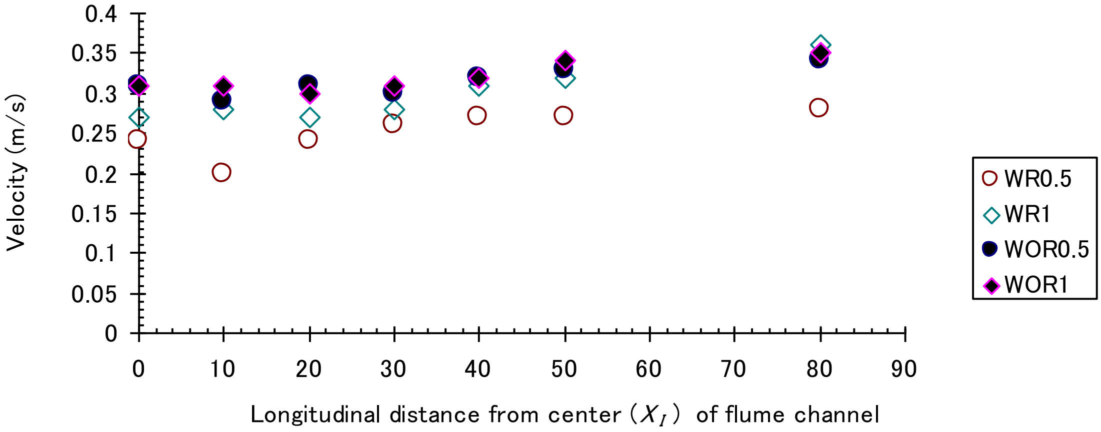


(b)



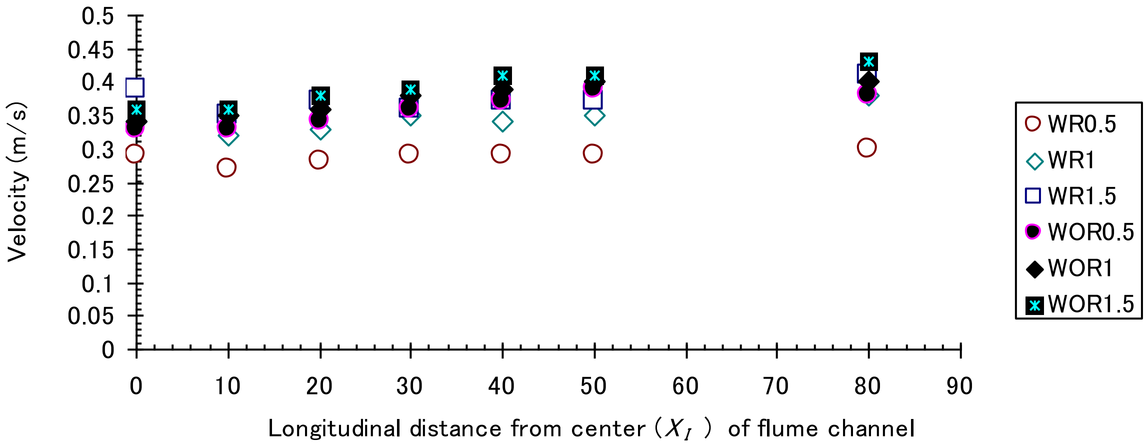
Velocity (m/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70
80
90
Longitudinal distance from center (X_I) of flume channel
○ WR0.5
● WOR0.5

(c)

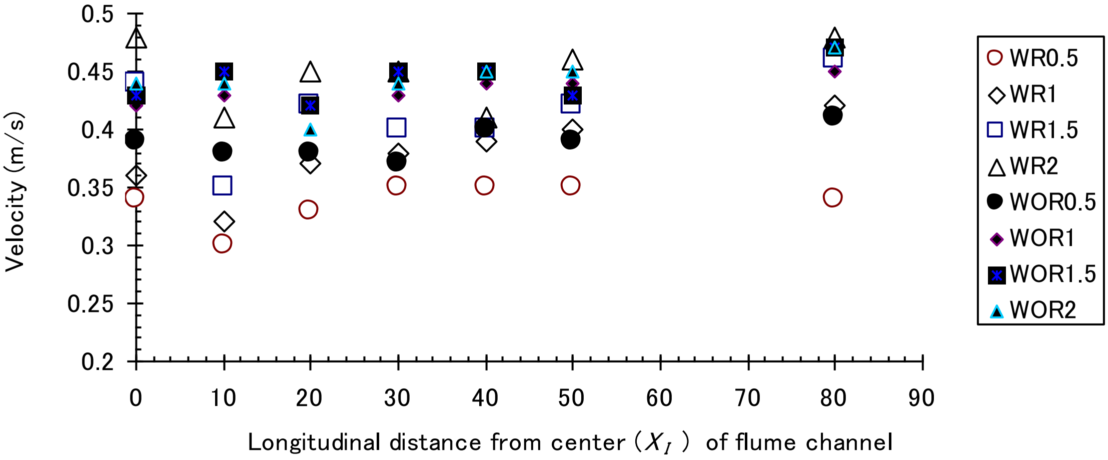


Velocity (m/s)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70
80
90
Longitudinal distance from center (X_I) of flume channel
○ WR0.5
◇ WR1
● WOR0.5
◆ WOR1

(d)



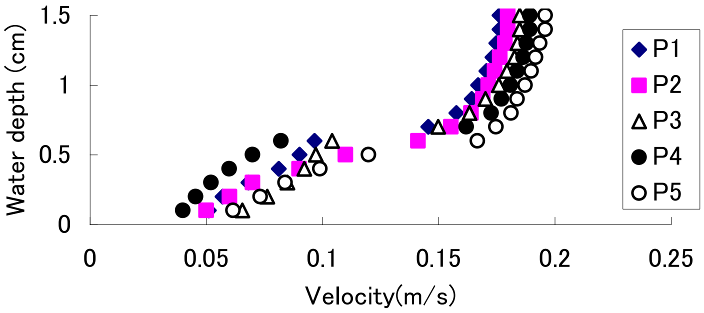
(e)



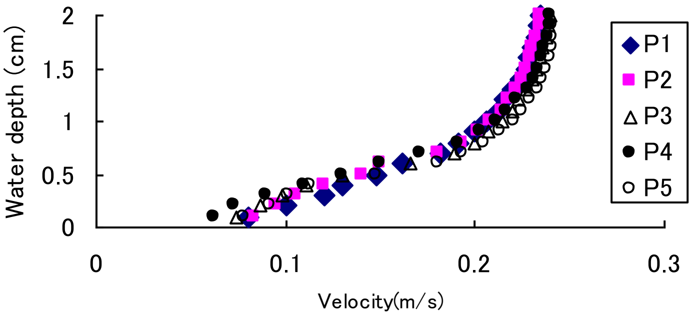
(f)

A2. velocity profile for (a)1.5cm water depth (b) 2cm water depth (c) 2.5cm water depth (d) 3m water depth (e)3.5cm water depth (f)4cm water depth; WOR-without roughness, WR-with roughness; WR0.5-with roughness at 0.5cm depth from bottom,WR1-with roughness at 1cm depth from bottom, WR1.5-with roughness at 1.5cm depth from bottom, WR2-with roughness at 2cm depth from bottom, , WOR0.5-without roughness at 0.5cm depth from bottom,WOR1-without roughness at 1cm depth from bottom, WOR1.5-without roughness at 1.5cm depth from bottom, WOR2-without roughness at 2cm depth from bottom,; For definition of X_I see Fig. 2.2

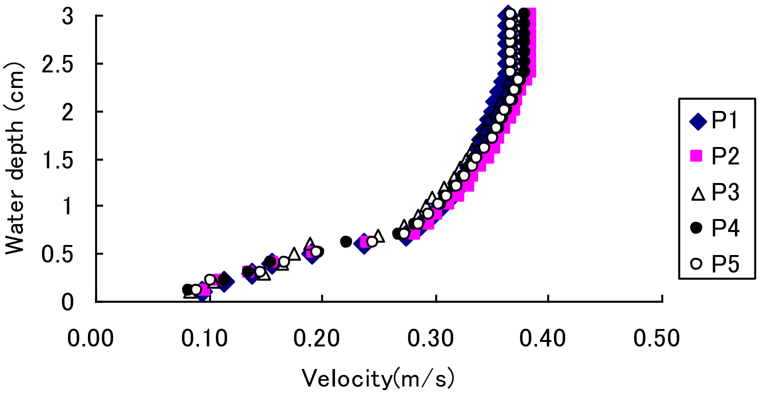
APPENDIX 3: Velocity profile in the flume (from PIV) for without roughness case (WOR)



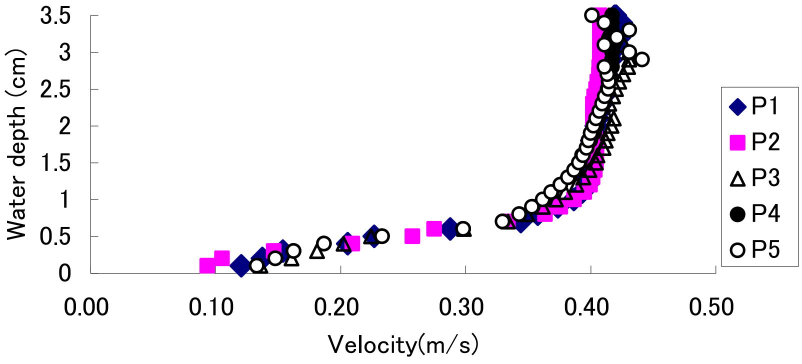
(a)



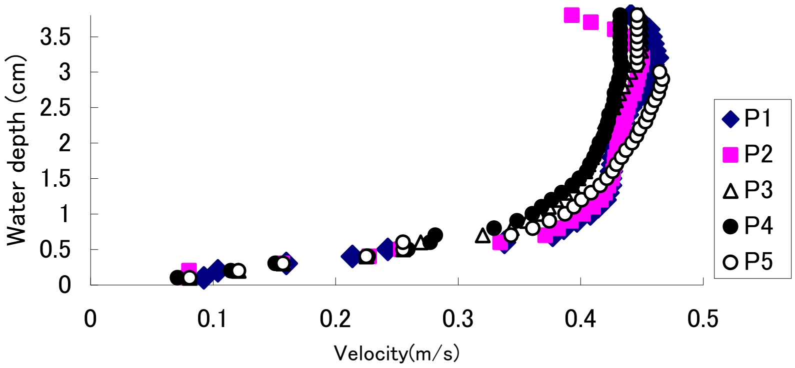
(b)



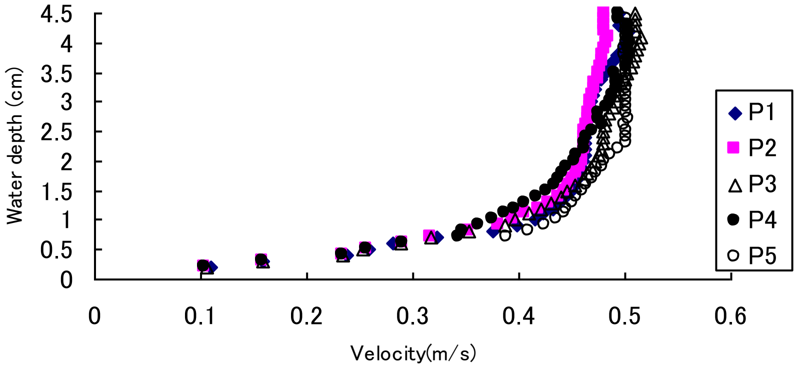
(c)



(d)



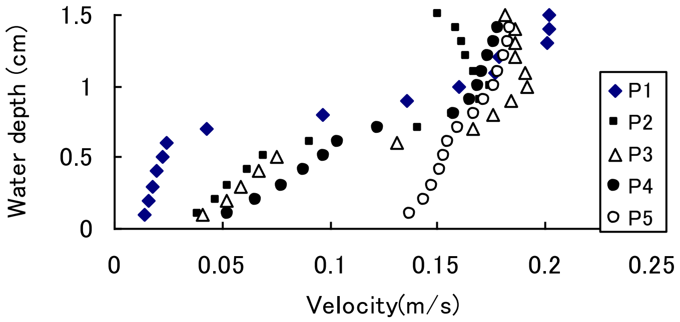
(e)



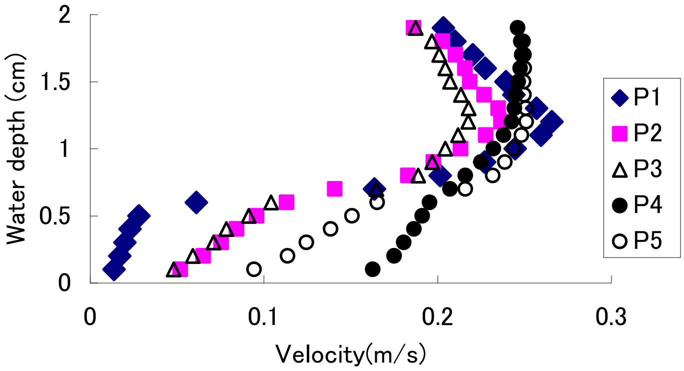
(f)

A3. Velocity profile for without roughness (WOR) from PIV (a) 1.5cm water depth (b) 2cm water depth (c) 2.5cm water depth (d) 3cm water depth (e)3.5cm water depth (f)3.8cm water depth (g) 4.5cm water depth ; See Fig. 2.9 and 2.12 for definition of P1, P2, P3, P4, P5

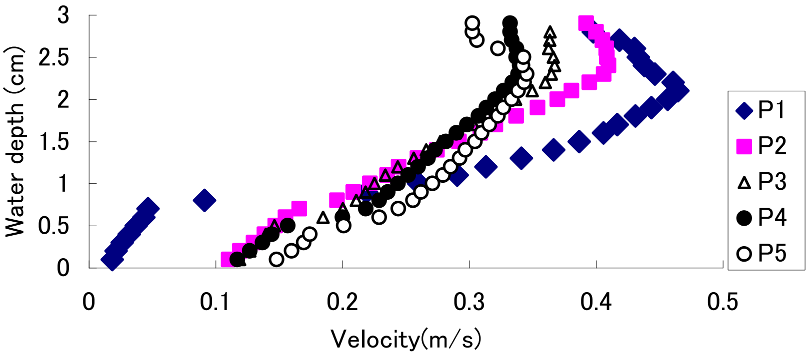
APPENDIX 4: Velocity profile in the flume (from PIV) for with roughness case (WR)



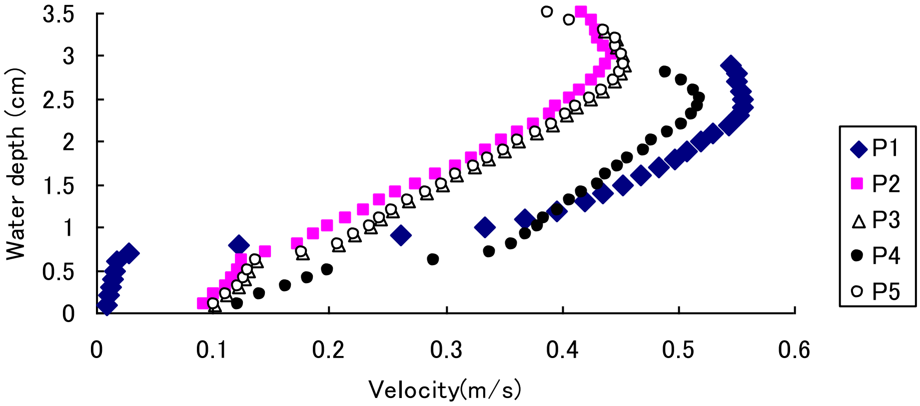
(a)



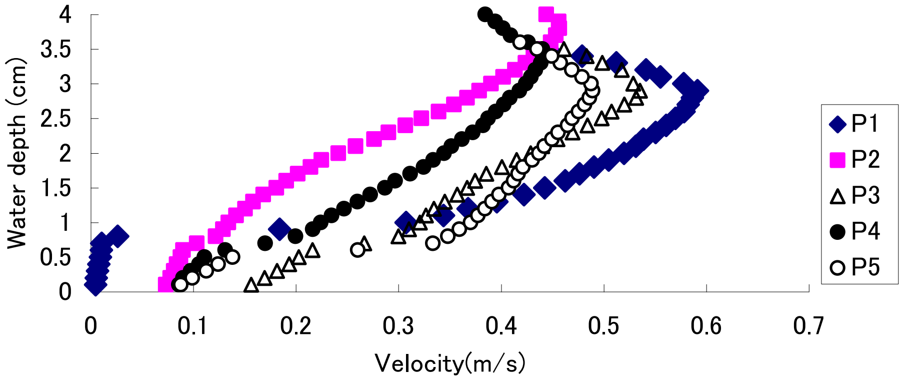
(b)



(c)



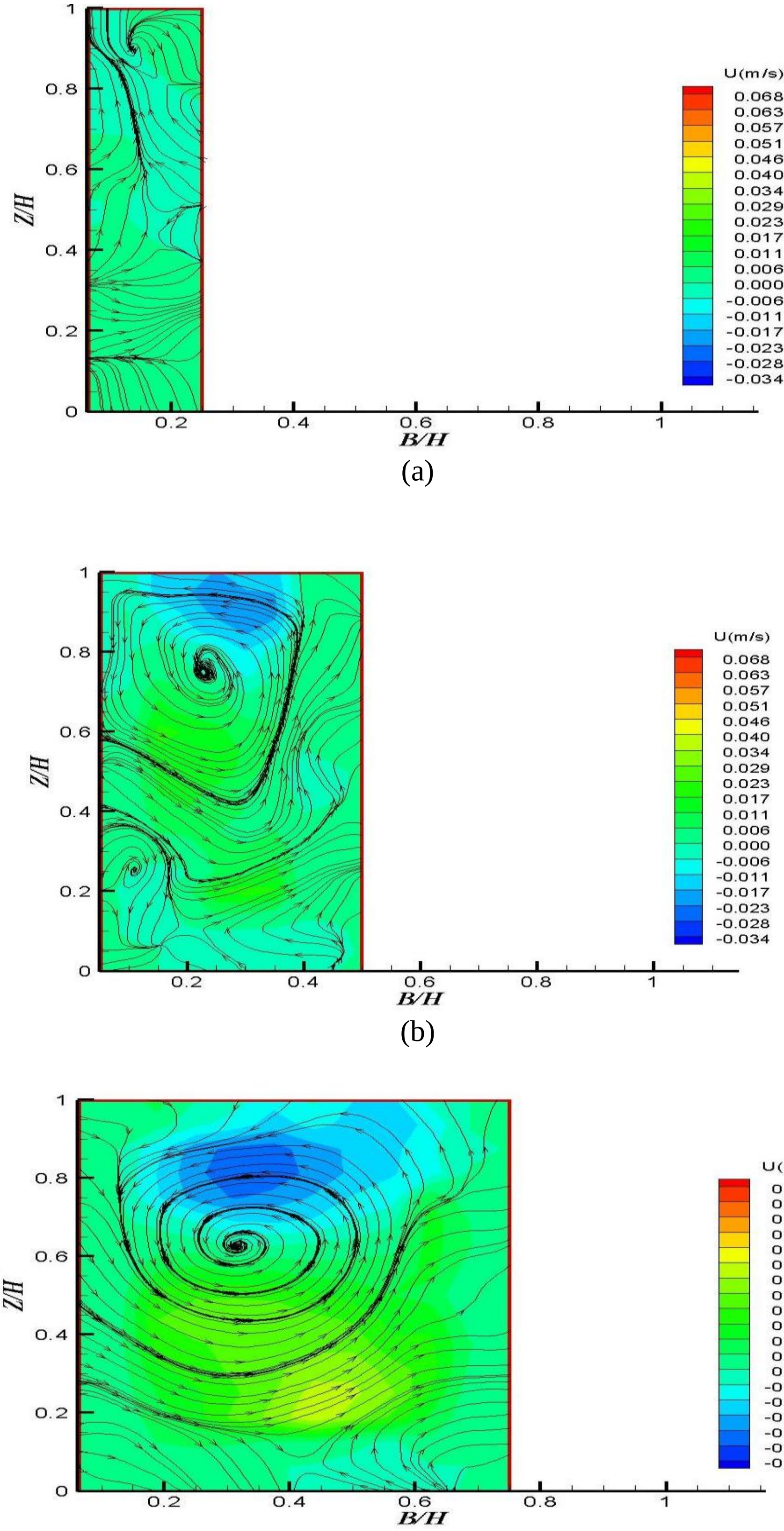
(d)



(e)

A4. velocity profile for with roughness (WR) from PIV (a)1.5cm water depth (b) 2cm water depth (c) 3 cm water depth (d) 3.5cm water depth (e)4cm water depth ; See Fig. 2.9 and 2.12 for definition of P1, P2, P3, P4, P5

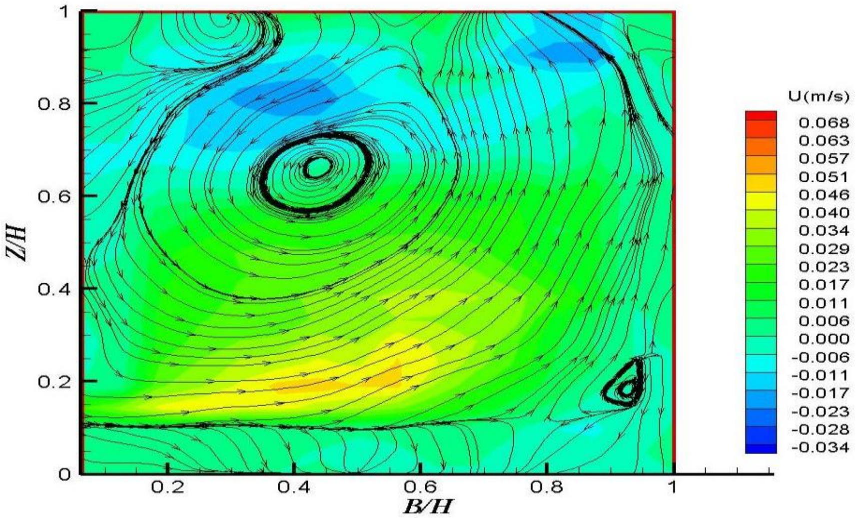
APPENDIX 5: Flow pattern inside the horizontal gap (Zone B) between 1st block and 2nd block for underscour depth (D_s/H) of 0.10, 0.15 and 0.20.



(a)

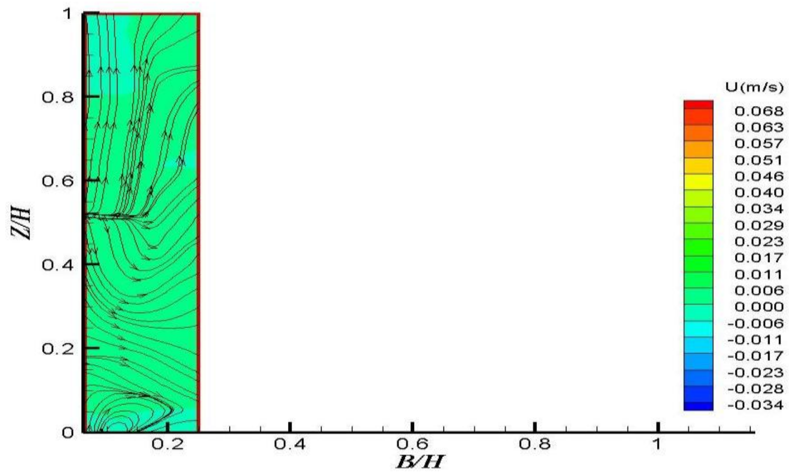
(b)

(c)



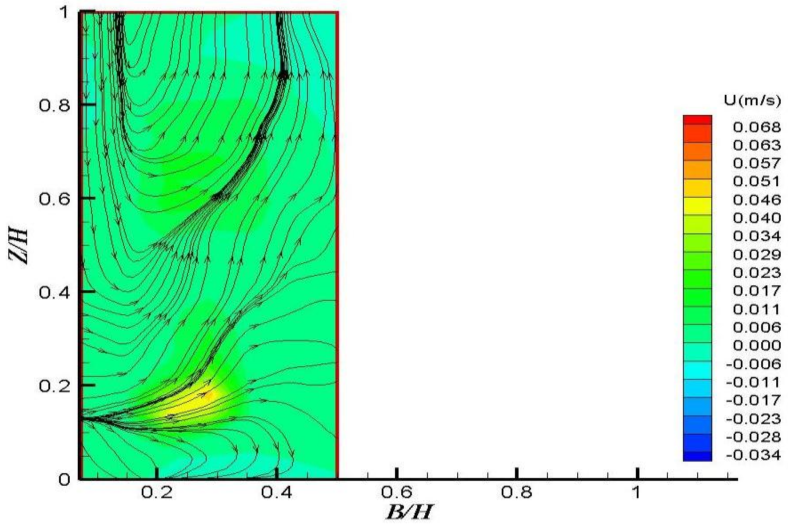
(d)

A5-1. Flow pattern in Zone *B* when non-dimensional underscour depth D_s/H is 0.10 and (a) *B/H*=0.25, (b) *B/H*=0.5, (c) *B/H*=0.75, and (d) *B/H*=1.0



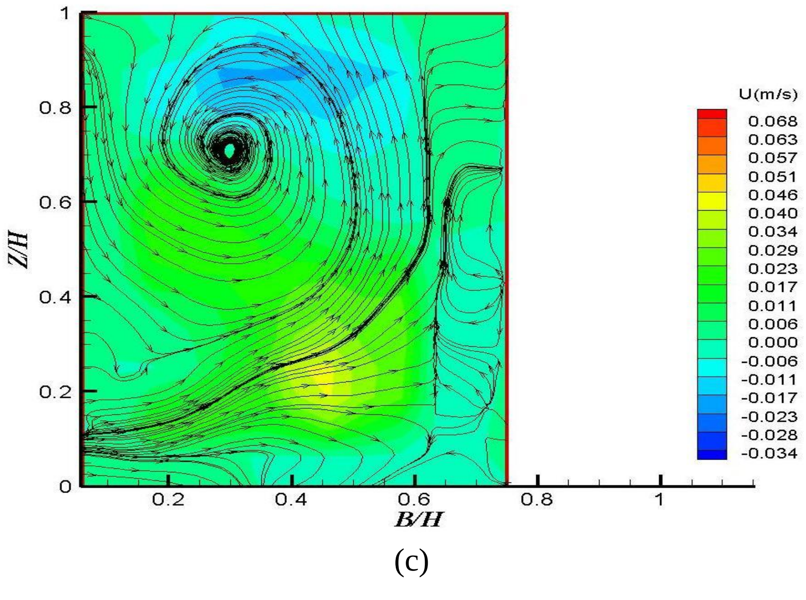
U(m/s)
0.068
0.063
0.057
0.051
0.046
0.040
0.034
0.029
0.023
0.017
0.011
0.006
0.000
-0.006
-0.011
-0.017
-0.023
-0.028
-0.034
Z/H
0
0.2
0.4
0.6
0.8
1
B/H
0.2
0.4
0.6
0.8
1

(a)



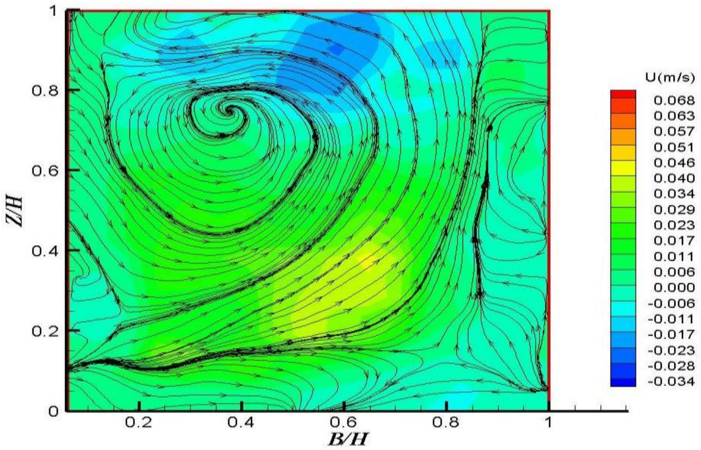
U(m/s)
0.068
0.063
0.057
0.051
0.046
0.040
0.034
0.029
0.023
0.017
0.011
0.006
0.000
-0.006
-0.011
-0.017
-0.023
-0.028
-0.034
Z/H
0
0.2
0.4
0.6
0.8
1
B/H
0.2
0.4
0.6
0.8
1

(b)



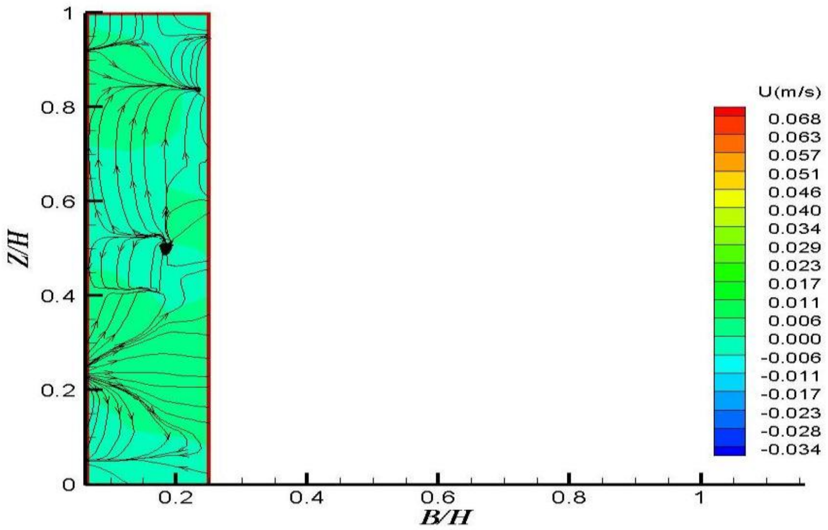
U(m/s)
0.068
0.063
0.057
0.051
0.046
0.040
0.034
0.029
0.023
0.017
0.011
0.006
0.000
-0.006
-0.011
-0.017
-0.023
-0.028
-0.034
Z/H
0
0.2
0.4
0.6
0.8
1
B/H
0.2
0.4
0.6
0.8
1

(c)

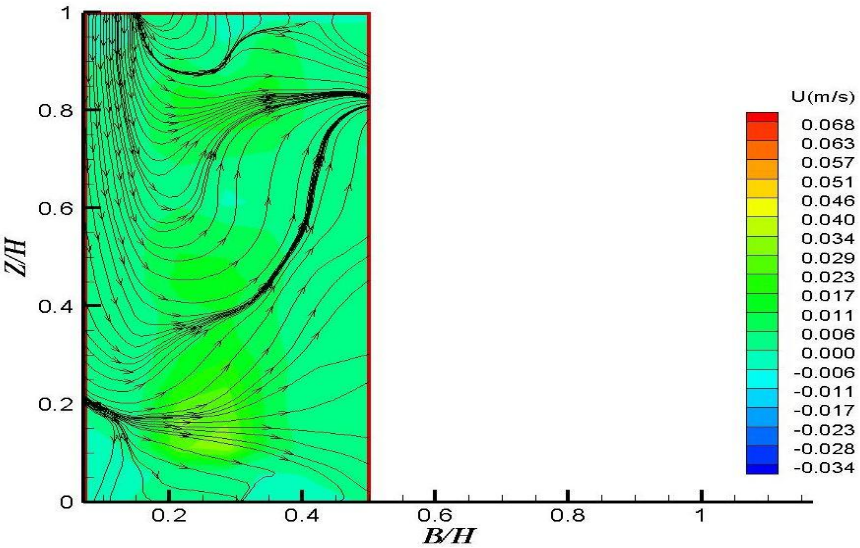


(d)

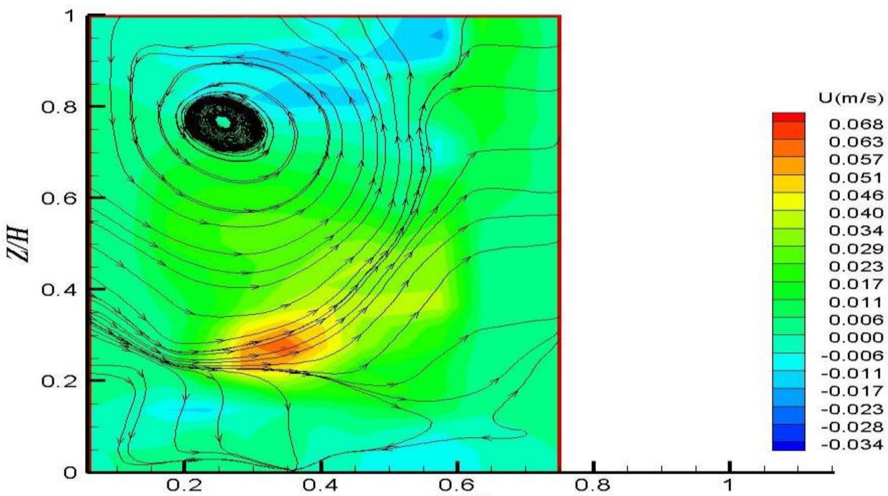
A5-2. Flow pattern in Zone *B* when non-dimensional underscour depth D_s/H is 0.15 and (a) B/H=0.25, (b) B/H=0.5, (c) B/H=0.75, and (d) B/H=1.0


U(m/s)
0.068
0.063
0.057
0.051
0.046
0.040
0.034
0.029
0.023
0.017
0.011
0.006
0.000
-0.006
-0.011
-0.017
-0.023
-0.028
-0.034
Z/H
0
0.2
0.4
0.6
0.8
1
B/H
0.2
0.4
0.6
0.8
1

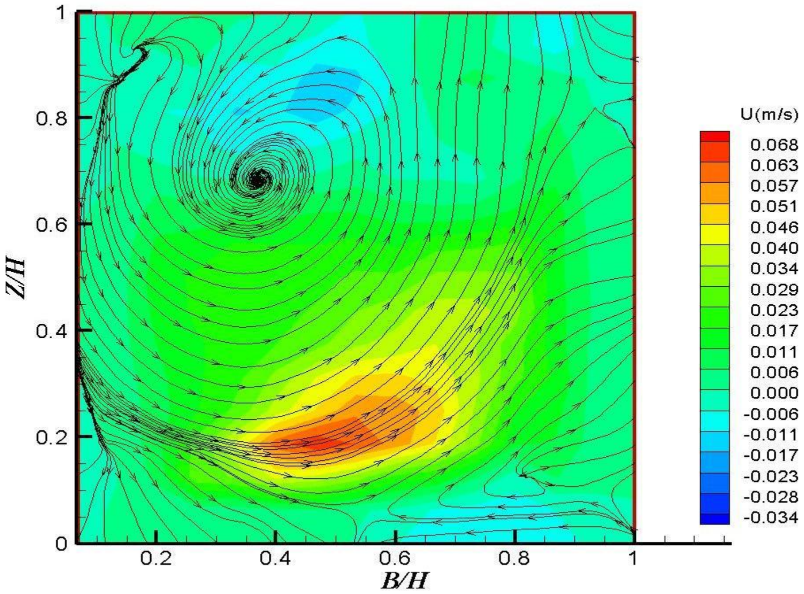
(a)


U(m/s)
0.068
0.063
0.057
0.051
0.046
0.040
0.034
0.029
0.023
0.017
0.011
0.006
0.000
-0.006
-0.011
-0.017
-0.023
-0.028
-0.034
Z/H
0
0.2
0.4
0.6
0.8
1
B/H
0.2
0.4
0.6
0.8
1

(b)


U(m/s)
0.068
0.063
0.057
0.051
0.046
0.040
0.034
0.029
0.023
0.017
0.011
0.006
0.000
-0.006
-0.011
-0.017
-0.023
-0.028
-0.034
Z/H
0
0.2
0.4
0.6
0.8
1
B/H
0.2
0.4
0.6
0.8
1

(c)



(d)

A5-3. Flow pattern in Zone *B* when non-dimensional underscour depth D_s/H is 0.20 and (a) *B/H*=0.25, (b) *B/H*=0.5, (c) *B/H*=0.75, and (d) *B/H*=1.0