Probabilistic entrainment of particles from a rectangular cavity in turbulent open channel flows

Prakash Agarwal

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**PROBABILISTIC ENTRAINMENT OF PARTICLES
FROM A RECTANGULAR CAVITY IN TURBULENT OPEN
CHANNEL FLOWS**

PRAKASH AGARWAL
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
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FROM A RECTANGULAR CAVITY IN TURBULENT
OPEN CHANNEL FLOWS**

PRAKASH AGARWAL

School of Civil and Environmental Engineering

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Summary

Entrainment of river-bed material from scour protection works such as grade control structures, has shown to have devastating consequences on the safety of hydraulic structures, as witnessed repeatedly in Taiwan's Toucian river during typhoon-induced floods. The entrainment of stones from between the gaps of the enormous concrete blocks used in these control structures has been the predominant factor behind their failure, with Lai et al. (2010) attributing gap scour to have been responsible for a massive 35.5% of the associated damages.

Although researchers in the past have studied sediment entrainment extensively, their studies have exclusively dealt with entrainment on flat sediment beds only, rather than from these cavities. The flow field in cavities such as gaps between these armor blocks can be highly turbulent and 3-dimensional, clearly in vivid contrast to the primarily unidirectional flow on flat beds. This spatial as well as temporal randomness in the turbulent cavity flow is likely to make the particle entrainment process highly probabilistic in nature, when compared to flat bed unidirectional flow fields which have low spatial variations near the sediment bed. Accordingly, experiments are conducted to investigate this entrainment phenomenon from a rectangular cavity using a frequentist probabilistic approach; and the role of different experimental parameters is examined to develop a comprehensive understanding of this stochastic entrainment process. The parameters used here are – particle characteristics, cavity depth, free-stream flow velocity, cavity length (or cavity aspect ratio).

Results from the experiments reveal that particle entrainment occurs over a wide range of particle properties and cavity depth, with varying degree of success, rather than 100% entrainment and no-entrainment being strictly demarcated by a critical or threshold value as was proposed by Sumer et al. (2001). The cavity flow field is seen to undergo significant transitions with increase in cavity depth, from 1-dimensional to 3-dimensional, with the latter comprising secondary flows, flow reversals, eddies, etc. The particle entrainment too is affected by this changing flow field, with entrainment probability following a reverse S-

shaped curve and entrainment durations following a lognormal distribution. The probabilistic aspect of this entrainment process is best highlighted when, despite keeping all test parameters constant, particles are still observed to entrain sometimes in 10 seconds, sometimes in 1 – 2 minutes, and at other times no entrainment occurs even for as long as 10 minutes duration.

The particle Shields parameter values (obtained from shear velocity in the free-stream region) are compared to the critical values in Shields (1936) and Sumer et al. (2001). The comparison reveals that particle entrainment from a cavity which is several times deeper than the particle diameter, can be attained even at Shields' parameter values significantly lower than the critical values proposed in these two studies. This aspect of the entrainment process becomes more apparent when the cavity flow fields are examined, which shows higher vertical velocity and higher turbulent kinetic energy (TKE) near the cavity downstream edge compared to that in the free-stream region. This is in spite of the lower streamwise velocity at the cavity edge. Visualization of the instantaneous vectors surrounding an entraining particle further reveals how intricately the entrainment is influenced by the randomness in the flow which is changing from one instant to another.

Finally, the effect of the cavity geometry on particle entrainment is studied in its entirety by keeping the cavity aspect ratio constant, but varying the cavity length and depth separately. It is observed that the cavity depth plays a more crucial role in determining the particle entrainment probability than the cavity length. Additionally, the cavity flow field is decomposed using the Proper Orthogonal Decomposition (POD) method to study the influence of cavity depth on the large-scale (LS) eddies. Although it would appear that particle entrainment from a shallower cavity is easier, the POD results show that the LS eddies at lower cavity depths have correspondingly lower TKE content due to the lower flow depth present at the cavity. These lower energy LS eddies in shallow depths sometimes negate the ease of entrainment from shallow cavities and lead to a reduced entrainment probability, especially for particles with relatively lower Shields parameter.

List of Publications

- [1] Agarwal, P. and Chiew, Y.-M. "Particle entrainment from a rectangular cavity in turbulent open-channel flows." *Advances in Water Resources* (under review).
- [2] Agarwal, P. and Chiew, Y.-M. "Cavity depth effects on the probability of particle entrainment." *Journal of Hydro-Environment Research* (under review).
- [3] Agarwal, P. and Chiew, Y.-M. "Effect of cavity configuration on particle movement, particle entrainment and the related cavity flow field." *Environmental Fluid Mechanics* (under review).
- [4] Guan, D., Agarwal, P., and Chiew, Y.-M. "Quadrant Analysis of Turbulence in a Rectangular Cavity with Large Aspect Ratios." *Physics of Fluids* (under review).

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List of Symbols

$a_{x,p}$	acceleration of particle in the x-direction
$a_{y,p}$	acceleration of particle in the y-direction
A_f	particle area exposed to the flow
C	sediment concentration
C_D	drag coefficient
C_L	lift coefficient
C_m	added mass coefficient
d	particle diameter
d^*	dimensionless particle size
d_{50}	median diameter
D	depth of rectangular cavity
D_s	mean stone size
e	particle protrusion
f_0	primary frequency of oscillation of switching jet
F_b	force due to buoyancy
F_g	force due to gravity
F_D	drag force
F_L	lift force
Fr_h	Froude number based on flow depth h
g	acceleration due to gravity
g_s	sediment flux
h	flow depth in the free-stream region
h_s	end sill height of vertical drop pool

h_{vd}	vertical drop height
H	flow depth at the cavity, i.e. $D + h$
I	impulse
L	length of rectangular cavity
L_D	moment arm of F_D about rotation point
L_L	moment arm of F_L about rotation point
L_p	length of vertical drop pool
L_W	moment arm of W about rotation point
m	mass of particle
n	total number of trials
N	set of natural numbers
p	particle entrainment probability
p_{ds}	downstream probability
$p_{et/ds}$	intermediate probability
P	pick-up probability of a particle
q^*	dimensionless bed-load transport rate
Q	flow discharge
Re	Reynolds number
Re_h	Reynolds number based on flow depth h
Re_{st}	stone Reynolds number
Re^*	boundary Reynolds number
Re_{cr}^*	critical boundary Reynolds number
s	specific gravity of a particle
s_b	bed slope
S'_t	weighted Strouhal number
t	time

t_e	entrainment time
T	timescale of suction of sediment from between stones
$\overline{T}_B$	mean-bursting period
$\overline{T}_e$	ejection period
$\overline{T}_s$	sweep period
T_p	dimensionless transport-stage parameter
T_t	macro-scale of turbulence
u	mean free-stream flow velocity
u_b	instantaneous velocity approaching to a bed particle
u_e	error in velocity in x-direction from PIV measurements
u_*	shear velocity
$u_{*,cr}$	critical shear velocity
u_{p0}	minimum initial vertical velocity for particle to lift upwards
u_{pf}	final velocity of particle at cavity top
v_e	error in velocity in y-direction from PIV measurements
v_t	particle terminal velocity
$v_{x,p}$	particle velocity in the x-direction
$v_{y,p}$	particle velocity in the y-direction
$ V $	flow velocity magnitude
V_p	particle volume
V_x	streamwise flow velocity (x-direction)
V_y	vertical flow velocity (y-direction)
V_z	spanwise flow velocity (z-direction)
V'_x	streamwise flow velocity fluctuation
V'_y	vertical flow velocity fluctuation

W	width of rectangular cavity
W_t	submerged weight of a particle
X	streamwise direction
y_0	roughness length
Y	vertical direction
Z	spanwise direction
Z_n	z-score of standard normal distribution
α	angle of attack
Δx	pixel dimension of the interrogation area (PIV) in x-direction
Δy	pixel dimension of the interrogation area (PIV) in y-direction
ε	error percentile
ϵ	divergence
κ	von Karman constant
Ω	momentum thickness
Φ_p	dimensionless pick-up rate
ρ	density of fluid
ρ_s	density of sediment or particle
τ	bed shear stress
τ_{cr}	critical bed shear stress
τ_{crg}	critical entrainment bed shear stress of a single grain
τ^*	Shields parameter
τ_{cr}^*	critical Shields parameter
$\tau_{cr-sumer}^*$	critical Shields parameter proposed by Sumer et al. (2001)
μ	dynamic viscosity of fluid
ν	kinematic viscosity of fluid

Chapter 1

Introduction

1.1 Background and motivation

Entrainment of bed material from between scour protection works, such as armor blocks, etc. has proven to have caused devastating consequences to the safety of river hydraulic structures. Typhoon induced floods in Taiwan's Toucian river have resulted in severe damage to the existing block grade control structures, thus putting in jeopardy the safety and integrity of nearby bridge piers. One of the major reasons behind the failure of these massive concrete armor blocks has been the entrainment of stones from between their gaps as shown in Fig. 1.1. Gap scour has been determined to be the dominant reason behind the grade structure failure contributing to 35.5% of the damage, followed by edge scour (22.6%), and head cutting and lateral erosion being the other minor failure modes (Lai et al., 2010).

Lai et al. (2010) have studied the gap scour effect by building a 1:50 scaled physical model and investigating the rate of erosion at different flow discharge conditions. However, their study addresses the erosion effect on a somewhat macro-scale without addressing the fundamental mechanism which brings forth this entrainment. Sumer et al. (2001) have attributed the sediment removal from between armor blocks to suction from vortices inside the gaps; and advocated the use of a deterministic model with a threshold Shields parameter value demarcating the suction and no-suction region. This approach in Sumer et al. (2001) is in contrast to the probabilistic mechanism that underpins the movement of sediment, resulting from the randomness in velocity fluctuations, eddy formation and turbulent bursting events.

Figure 1.1 Block grade control structure on the Toucian river: (a) before; and (b), (c), (d) after floods.

Apart from Sumer et al. (2001) and Lai et al. (2010), many researchers in the past have extensively studied sediment entrainment but exclusively on flat sediment beds, and not from gaps or cavities. Whereas in such past studies, 'entrainment' simply implies sediment motion or movement from its initial position; in the present study, 'entrainment' refers to sediment escaping from a cavity, which may include significant streamwise, vertical and spanwise movements several times the particle diameter, depending on the cavity dimensions. Thus, what is meant by 'entrainment' in past studies is only the first small step in a particle's path to entrainment from a cavity in this present study. Furthermore, the flow field in earlier works on flat sediment beds may be considered primarily 1-dimensional, whereas the flow field in a cavity or gap is more likely to be 3-dimensional with their own secondary flows and eddies playing a significant role in the cavity flow field characteristics.

The flow field in a rectangular cavity is largely dependent on the cavity dimensions as well as the global flow parameters, and this has been investigated extensively by past researchers, such as Haigermoser et al. (2008), Lin and Rockwell (2001), Faure et al. (2009), Cicca et al. (2013), and many others. However, particle entrainment from such a rectangular cavity with its probabilistic aspects has, as yet, not been studied; Sumer et al. (2001) and Lai et al. (2010) have conducted investigations, but with its own limitations as addressed previously. It is this missing gap that the present research aims to investigate by adopting a frequentist probabilistic approach to particle entrainment from a rectangular cavity, and probing the effect of different test parameters on this particle entrainment phenomenon.

However, it is to be noted that the cavity used in this current study is not a physical replica of the grade-control structure; instead it is a regular shaped rectangular shallow cavity, which can be seen as a generalized form of the gaps found in these scour-protection works. This is so because the primary objective of the present study is to examine the fundamental features that affect this particle entrainment phenomenon, rather than provide specific design guidelines for building these scour-protection structures. Nevertheless, the grade-control structures in Taiwan, and the studies of Sumer et al. (2001) and Lai et al. (2010) definitely serve as a motivation behind the present work. Additionally, this entrainment phenomenon studied on a fundamental level, has the advantage of it being potentially extended to other areas, such as erosion from scour holes in the vicinity of water jet exits,

ship propellers, bridge piers, submarine pipelines; as well as to explain the formation and movement of dunes and anti-dunes.

1.2 Layout of the thesis

This thesis comprises seven chapters, and a brief description of these is given below:

1. In the current chapter, i.e. Chapter 1, the background of the topic and motivation behind undertaking this present work is introduced, and organization of the thesis presented.
2. Chapter 2 reviews published literature in the field of sediment incipient motion (deterministic and probabilistic studies), role of flow structures in such entrainment, as well as studies dealing with just the flow physics in a rectangular cavity without the associated entrainment phenomenon. Studies by Sumer et al. (2001) and Lai et al. (2010) are covered in greater details because of their higher relevance to the present topic.
3. Chapter 3 describes the experimental set-up, the instrumentation used for flow measurements (acoustic devices as well as laser imaging techniques) and the methodology for calculating particle entrainment probabilities.
4. Chapter 4 presents a brief conceptual model describing the various possible flow fields that a particle inside a cavity can be subjected to. The chapter also analyzes the experimental results for Series 1 where only the cavity depth is used as a variable - the entrainment probability values, entrainment timescales and the plan-view particle trajectories are discussed.
5. Chapter 5 discusses the results from test Series 2 in which the free-stream flow velocity is varied, while all other parameters are kept constant. Flow fields obtained from PIV measurements are presented in this chapter, and an entraining particle's motion from the cavity bed to the cavity top is more closely scrutinized.
6. Chapter 6 compares particle entrainment probabilities from cavity configurations having the same aspect ratio (L/D) but different depths (D) in one set and different

lengths (L) in another set. The cavity flow fields in this test Series 3 obtained from PIV measurements are also presented in this chapter.

7. Chapter 7 presents the conclusions drawn from this study and provides recommendations for future work.

Chapter 2

Literature review

2.1 Introduction

Studies in incipient motion of sediment transport have been continuing for decades with Shield's work (Shields 1936) holding the twin recognition of being one of the earliest and also the most widely used in the area of incipient sediment motion. Although sediment entrainment was initially conceptualized as a deterministic phenomenon with the possibility of motion being determined by a fixed threshold shear stress value, the entrainment process is now fairly ensconced as a stochastic process instead; with Einstein's (1942) study being one of the pioneering works in adopting the probabilistic approach.

The movement of sediment such as that in armored river beds can prove to be detrimental to the safety of river bed structures such as bridges, as has been repeatedly witnessed in Taiwan with typhoon induced floods uprooting armored blocks from the river bed. Sumer et al.'s (2001) paper attributes the removal of sediment from between armor blocks to suction and accordingly proceeds with a deterministic method for investigating the problem. It is this deterministic approach that will be improved upon in this study by using experimental investigations and adopting a probabilistic approach.

This literature review provides a necessary foundation by reviewing published works in the field of incipient sediment motion before embarking on bridging some important gaps left unexplored by current research. The remaining chapter is divided into the following sections – Section 2.2 introduces Shields' deterministic model for incipient motion and Section 2.3 deals with the probabilistic approach and the critical impulse concept adopted by different researchers. Section 2.4 describes Sumer's deterministic experimental model and other researchers' recent experiments on sediment entrainment. These include studies that examine the importance of coherent structures (2-dimensional quadrant analysis as well as 3-dimensional octant analysis), turbulent bursting, and large scale flow structures. Cavity

flows are routinely encountered in hydraulic structures and mechanical configurations alike. Consequently, many experimental studies have been conducted in this area on deep as well as shallow cavities. Results from these studies are presented in Section 2.5. The chapter ends with Section 2.6, providing some concluding remarks on the literature reviewed and the gaps encountered, thus paving the way for the next stage of addressing the problems and issues raised herein.

2.2 Threshold criteria for incipient motion

The threshold criterion for sediment movement may be defined as the minimum shear stress required to move a particle of a given size and density, or the maximum particle size that can be moved with a particular shear stress value; the latter being referred to as the competence approach.

2.2.1 Shields diagram for incipient motion

To study incipient motion, Shields (1936) makes use of the sediment transport rate which he extrapolates to zero value and terms the corresponding shear stress as the critical or threshold shear stress below which no motion has supposedly taken place. The Shields diagram (Fig. 2.1) represents Shields dimensionless critical shear stress (τ_{cr}^*) as a function of critical boundary Reynolds number (Re_{cr}^*) (Shields 1936) where

$$\tau_{cr}^* = \frac{\tau_{cr}}{(\rho_s - \rho)gd} \quad (2.1)$$

$$Re_{cr}^* = \frac{u_{cr}^* d}{\nu} \quad (2.2)$$

and, τ_{cr} , τ_{cr}^* , ρ , ρ_s , g , d , u_{cr}^* and ν are the critical bed shear stress, the corresponding dimensionless critical shear stress, fluid density, sediment density, gravitational acceleration, particle diameter, critical shear velocity for incipient motion and kinematic viscosity of the fluid, respectively. In addition, the critical shear velocity is related to the critical bed shear stress by the relation:

$$u_{cr}^* = \sqrt{\frac{\tau_{cr}^*}{\rho}} \quad (2.3)$$

Figure 2.1 τ_{cr}^* (using median grain size) as a function of Re_{cr}^* , redrafted from Shields (1936). Shaded band with irregular boundaries is data envelope and curve fit as defined by Shields. Solid and dashed lines are later fits of these data by Rouse (1939, 1949) and Henderson (1966) respectively. Note that Gilbert (1914) and USWES (1935) values are actually for $\tau_{cr\bar{m}}^*$ (using mean grain size) which differs from that of τ_{cr}^* only for USWES. (Reproduced from Buffington, 1999)

In the above figure, while Henderson's (1966) curve fits accurately to the Shields data arriving at the critical stress value of 0.056 for $Re_{cr}^* > 1000$, Rouse's (1939, 1949) curve deviates at higher Re_{cr}^* giving the critical stress as 0.06 as suggested by Shields. Although it is widely believed that Shields' critical shear stress value corresponds to zero bed-load transport rate, Buffington (2000) shows that the dimensionless bed-load transport rate (q^*) in fact varies from 10^{-4} to 10^{-1} (Fig. 2.2) due to inconsistencies in specifying a particular transport rate for defining incipient motion. Similar work on bed-load transport in cohesionless sediments has also been done by Liu and Chiew (2012) under the effects of seepage.

Figure 2.2 Shields parameter (τ^*) versus boundary Reynolds number (Re^*) showing the range of bed-load transport rate varying from 10^{-4} to 10^{-1} rather than sticking to an exact zero transport rate. (Reproduced from Buffington, 2000)

It can be observed from Figure 2.1 that the original Shields curve provides the critical shear stress only for a limited range of Re_{cr}^* that varies from 2 to 500. This limited range in the Shields diagram is updated and modified by Miller et al. (1977) by incorporating more recent data and Re_{cr}^* is extended by three orders of magnitude (Fig. 2.3).

Figure 2.3 The modified Shields curve based on additional data (Reproduced from Miller et al., 1977)

2.2.2 Common methods for defining incipient motion

Although Shields (1936) uses the reference-based method to define incipient motion, researchers have made widespread use of other methods, such as the competence method (based on selective transport of particles), the theoretical method (based on force balance), and the visual-based method. The visual-based method can be again sub-divided into four main categories (Kramer, 1932):

- No transport – no movement of particles;
- Weak transport – movement of few particles witnessed at isolated points;
- Medium transport – movement of many sediment particles but having small discharge; and
- General transport – movement of all particles at all times at all locations.

Buffington and Montgomery (1997) have reviewed extensive incipient motion studies, and made a comparative plot of the Shields diagram using the reference based method and the visual based method (Fig. 2.4). The plot shows the upper and lower limits of the critical stress for the reference based method to be higher than that for the visual based method. The plot is evidence enough of the inconsistencies among researchers in defining and quantifying the threshold criteria for incipient motion.

One of the major sources of such ambiguities may also be attributed to the bed condition. In reference based studies, measurements being conducted after the attainment of equilibrium may correspond more likely to a rippled bed with bed forms affecting the results; whereas visual studies remain unaffected because of observations being conducted on a planar bed free of bed forms. Flume beds with bed forms lead to a cyclic process wherein the flow leads to formation of ripples, dunes, etc and these bed forms in turn affect the flow patterns, resistance to flow, etc.

For a comprehensive discussion and comparison of the four methods, one may refer to Kramer (1932, 1935), Lavelle and Mofjeld (1987), Buffington and Montgomery (1997),

Buffington (1999). See also Vanoni et al. (1966), Miller et al. (1977), Yalin and Karahan (1979) for additional reviews on the threshold stress concept and experimental data.

Figure 2.4 Comparison of critical shear stress using the reference-based (upper figure) and visual-based (lower figure) methods. (Reproduced from Buffington and Montgomery, 1997)

2.2.3 Disagreements over the threshold approach

The non-existence of a critical threshold shear stress value has been made evident from the experimental study of Paintal (1971a) where experiments are conducted near the critical stress region and compared with experiments done at relatively higher stresses (Gilbert, 1914; USWES, 1935; Johnson, 1943). Plots between dimensionless bed-load transport rates (q^*) and dimensionless bed shear stress (τ^*) show sediment movement even below

threshold values, with higher scatter at lower stresses (Fig. 2.5). The author points out that fluctuations in the turbulent fluid forces, varying particle embedment, particle protrusion and other factors lead to random sediment motion both in space and time, and concludes that there is no stress value corresponding to zero motion, but one has to simply observe for longer durations of time. Two relationships are provided with one applicable to low stress values (below 0.05) and the other for stresses higher than 0.05 as shown below:

$$q^* = (6.56 * 10^{18}) \tau_*^{16} \quad \text{for } \tau_* \leq 0.05 \quad (2.4)$$

$$q^* = 13 \tau_*^{2.5} \quad \text{for } \tau_* > 0.05 \quad (2.5)$$

Figure 2.5 Bed load transport at low shear values (Reproduced from Paintal, 1971 a)

The futility of defining a threshold criterion has also been well addressed by Lavelle and Mofjeld (1987), where the authors match non-cohesive sediment transport values based upon the critical stress concept, with their stochastic model (without threshold) using Guy et al.'s (1966) experimental data on cohesive sediments. In their model, the authors calculate the sediment flux (g_s) using:

$$g_s = \int_{y_0}^h (uC) dy \quad (2.6)$$

where y_0 , h , u , C and y represents the roughness length, flow depth, streamwise flow velocity, sediment concentration and vertical coordinate (positive upwards), respectively. Furthermore, their model makes use of no reference concentration at any point near the bed, thus obviating the need to specify a threshold criterion. The above equation is used to

calculate the flux with input data from Guy et al. (1966); and model and experimental results are plotted on a graph (Fig. 2.6), which shows a close fit.

Figure 2.6 Results of Lavelle and Mofjeld's (1987) model without threshold criteria versus Guy et al.'s (1966) laboratory data using threshold criteria (Reproduced from Lavelle and Mofjeld, 1987)

The authors also get close approximation when they compare their model's erosion rate with Van Rijn's (1984) experimental data on non-cohesive sediments with no threshold criterion used.

From the discussion and the scatter points observed in the plots above, one may clearly conclude that identifying the threshold for incipient motion is fraught with many challenges. Experiments have recorded movement well below the critical stress value of 0.06 (as advocated by Shields, 1936). Vanoni et al. (1966), Paintal (1971a), amongst others, observe that motion can occur far below the threshold stress value, even at 0.01, notwithstanding the still lower stresses at which movement is possible with observation times approaching hours and days.

The turbulence generated by the impingement of eddies on the bed and the subsequent development of instantaneous forces with their wide temporal and spatial variation can enable flows even with smaller magnitudes to move the sediment from their at-rest

positions. This raises the question on whether sediment incipient motion can be adequately addressed by employing a deterministic approach and whether or not a threshold value really exists below which no motion takes place. Disagreements over arriving at a fixed threshold stress value has paved the way for the probabilistic approach to model this stochastic phenomenon of sediment incipient motion using instantaneous values, as will be discussed in the following section.

2.3 Probabilistic approaches to sediment motion modeling

Past studies (Grass, 1970; Cheng and Chiew, 1998; Wu and Lin, 2002; Wu and Chou, 2003; etc.) have used probability distributions for a variety of parameters starting from the bed shear stress, flow velocity, particle protrusion, etc and employed the force balance methods to calculate the pick-up probabilities for different modes of particle motion – rolling, sliding, and lifting. Discrete Particle Modeling (McEwan and Heald, 2001; McEwan et al., 2004; etc) has also been used to study sediment entrainment and calculate pick-up probabilities, taking into account the minutest details of the process such as particle-to-particle interactions and collisions, bed geometry, sediment packing, flow parameters, etc.

2.3.1 Use of bed shear stress distributions

Grass (1970) has attempted to generalize the solution to describe initial motion of sediment grains by using statistical distributions of resisting stress by the grains and the applied stress by the fluid turbulence. He uses a measured distribution of critical instantaneous bed shear stress associated with grain movement (as block histograms) and an experimentally derived smooth distribution of instantaneous bed shear stress for 2-dimensional channel flow type (Fig. 2.7). The critical flow condition is arrived at by equating the lower range of critical shear stress to the upper range of shear stress for a particular flow type; with entrainment occurring in the overlapped region of the two distributions and spasmodic bursts of entrainment occurring beyond the critical value ($\overline{\tau_{cr}}$) due to near bed turbulence. Thus, instead of using a threshold shear stress concept or quantifying the number of grains in motion, the author employs experimentally derived distributions to develop a generalized framework for defining incipient motion.

Figure 2.7 Distributions of instantaneous bed shear stress (τ) for 2-dimensional channel flow (smooth curves) placed relative to measured distributions of instantaneous critical bed shear stress associated with bed material (block histograms), where n'/N represents fraction of critical shear stress values falling in a particular shear stress interval.

(Reproduced from Grass, 1970)

2.3.2 Pick-up probabilities

Einstein (1950) has theoretically calculated the pick-up probability (P) of a bed particle based on the force balance between its submerged weight (W_t) and the normally distributed lift force (F_L) it experiences due to the fluid flow. Using the condition $F_L > W_t$, he arrives at

$$P = 1 - \int_{-\frac{0.143}{\tau^*}-2}^{\frac{0.143}{\tau^*}-2} \frac{1}{\sqrt{\pi}} \exp(-\chi^2) d\chi \quad (2.7)$$

where χ represents the variable of integration.

The subsequent bed-load formula calculated by Einstein (1950) has been further modified in Wang et al. (2008) taking into account the model's step length, exchange time and the lifting threshold. The modified equation which is applicable to both uniform and mixed sediment bed, gives good results when compared with experimental and field data.

Fredsoe and Deigaard (1992) have also calculated the pick-up probability (P) by empirically fitting the experimental datasets of Luque (1974) and Guy et al. (1966), to arrive at the following relation

$$P = \left[1 + \left(\frac{0.419}{\tau^* - 0.045} \right)^4 \right]^{-0.25} \quad (2.8)$$

However, it should be noted that the above equation is rendered useless when $\tau^* \leq 0.045$.

Cheng and Chiew (1998) noted that the widely varying nature of the instantaneous forces to which the bed particle is subjected, is due to flow turbulence, and accordingly, incorporated it in their derivation of the pick-up probability using the condition $P = P(F_L > W_t)$ and the assumption of the flow velocity being normally distributed, to arrive at the relation:

$$P = 1 - 0.5 \frac{B - \bar{u}_b}{|B - \bar{u}_b|} \sqrt{1 - \exp \left[-\frac{2(B - \bar{u}_b)^2}{\pi \sigma^2} \right]} - 0.5 \sqrt{1 - \exp \left[-\frac{2(B + \bar{u}_b)^2}{\pi \sigma^2} \right]} \quad (2.9)$$

$$\text{with } B = \sqrt{\frac{4(\rho_s - \rho)gd}{3\rho C_L}}; \sigma = \sqrt{(u_b - \bar{u}_b)^2}$$

where d , C_L , u_b and $\bar{u}_b$ are the particle diameter, lift coefficient, instantaneous flow velocity and the time mean value of the instantaneous flow velocity respectively.

When compared to the theoretical formula by Einstein (1950) and the empirical equation by Fredsoe and Deigaard (1992), Cheng and Chiew (1998) shows that the former over-predicts the pick-up probability when compared with the measured data (Fig. 2.8). Moreover, the

much discussed threshold shear stress values of 0.05 and 0.06 correspond to pick-up probabilities 0.6% and 2%, respectively when $C_L = 0.25$, implying that the Shields threshold criterion of incipient motion $\tau_{cr}^* = 0.05$ will dislodge 0.6% of all the particles in a given bed area from their at-rest position into instantaneous motion.

Figure 2.8 Comparison of pick-up probability (Cheng and Chiew, 1998) with that of Einstein (1950) and Fredsoe and Deigaard (1992) (Reproduced from Cheng and Chiew, 1998)

Cheng and Chiew's (1998) approach is adapted by Wu and Lin (2002) by using a log-normal distribution for the instantaneous streamwise flow velocity instead of the Gaussian distribution. The use of a lognormal distribution for flow velocity is also championed by Lopez and Garcia (2001) and Kalinske (1947); whereas Christensen (1965) and Yalin (1977) advocated the use of normal distribution for velocity fluctuation components in rough turbulent flows. This revision restricted the approach velocity to having a positive magnitude as per Nelson et al. (1995). The analytically modified pick-up probability (P) obtained by Wu and Li (2002) is given in Eqn. 2.10 and its comparison with experimental

data is shown in Fig. 2.9 below. The figure shows that the modified results using the lognormal distribution have a significant improvement over that for the normal distribution. The overall improvement in accuracy is estimated to be at the level of 51%. However, it is to be noted that data used for validation is quite limited, especially for the range of high τ^* .

$$P = 0.5 - 0.5 \frac{\ln \left(\frac{0.049}{C_L \tau^*} \right)}{\left| \ln \left(\frac{0.049}{C_L \tau^*} \right) \right|} \sqrt{1 - \exp \left\{ -\frac{2}{\pi} \left[\frac{\ln \left(0.049 / C_L \tau^* \right)}{0.702} \right]^2 \right\}} \quad (2.10)$$

Figure 2.9 Comparison of Wu and Lin's (2002) pick-up probability with experimental data (Reproduced from Wu and Lin, 2002)

2.3.3 Empirical pick-up functions

Van Rijn (1984) has conducted experimental studies with cohesionless sediment to come up with an empirical pick-up function for comparison with results from five other researchers namely, Einstein (1950), Yalin (1977), de Ruiter (1982, 1983), Nagakawa and Tsujimoto

(1980), and Luque (1974). The author follows Yalin's (1977) pick-up definition and uses visual observations to determine the beginning of incipient sediment motion. The sediment pick-up rate is calculated in mass per unit area and time, and the dimensionless pick-up rate (Φ_p) is presented as:

$$\Phi_p = 0.00033(d^*)^{0.3}(T_p)^{1.5} \quad (2.11)$$

where d^* and T_p are the dimensionless particle parameter and the dimensionless transport-stage parameter respectively. The comparison of the above studies for sediment diameters from 0.13 mm – 1.5 mm shows different amounts of variability, with results from Einstein (1950) and Yalin (1977) giving the poorest match and the remaining three studies providing good matches only for small or large particle sizes; but none of the five studies seem to produce good matches for all the sizes used in the experiment. Such incongruities between theoretical and experimental results highlight the still prevalent ambiguity even in the stochastic definition of the sediment transport phenomenon.

2.3.4 Bed embedment models

Although Einstein (1950) and Kalinske (1947) made use of the normal distribution for lift force and velocity fluctuations respectively in their probability model, sediment motion is also influenced by particle exposure, protrusions and embedment of a particle relative to its neighboring ones. This effect of bed embedment is dealt with in Paintal (1971b) who formulates an analytical model using a uniform distribution for the exposure of the particle in question and its neighbors. However, the maximum value of mean probability of movement attained by the model is limited to 0.68 even at very high shear stresses. The author cautions that this maximum value may not hold steady under practical situations of high shear stress conditions, and the ambiguity is a result of the model chosen in the study, rather than it representing any limit in the real phenomenon. The model is further extended to derive a relation between the transport rate and shear stress and compared with the bed-load equations of Einstein (1950), Kalinske (1947), and Meyer-Peter (1948). It is worth noting from Figure 2.10 that only Paintal's (1971b) model gives bed load movement below the supposedly critical shear stress value of 0.05.

Figure 2.10 Comparison of bed-load equation (Paintal, 1971b) with other researchers' equations (Reproduced from Paintal, 1971b)

Sediment entrainment can occur in any of the three modes – sliding (Paintal 1971b), lifting (Einstein, 1950; Cheng and Chiew, 1998; Wu and Lin, 2002) or rolling. Wu and Chou (2003) calculates the roll, lift and total pick-up probabilities taking into account grain exposure (δ) by developing a bed grain geometry model (Fig. 2.11) and using the threshold conditions as follows:

$$F_L > W_t \quad (\text{lifting threshold}), \quad (2.12)$$

$$F_D L_D + F_L L_L > W_t L_W \quad (\text{rolling threshold}) \quad (2.13)$$

where F_D , L_D , L_L , and L_W are the instantaneous drag force, moment arms (about C) of F_D , F_L and W_t respectively (see Fig. 2.11).

**Figure 2.11 Longitudinal section of the bed grain geometry with forces on particle
(Reproduced from Wu and Chou 2003)**

The roll, lift and total entrainment probabilities have been expressed as a function of the dimensionless shear stress (τ^*) in Figure 2.12. The figure shows the roll probability exceeding the lift probability and contributing almost 90% to the total entrainment probability till τ^* is 0.05. The study also finds no consistent probability of entrainment corresponding to any critical shear stress values calculated using the thresholds predicted in Ling (1995).

For a comprehensive modeling of the bed grain geometry, the horizontal orientation of the bed surface structure has also been investigated in addition to the particle's vertical protrusion. The combined effect of these two parameters has been studied by Chin and Chiew (1993) where the authors use the angle of attack (α) of the undisturbed approach flow to represent the particle's horizontal orientation. Apart from reporting a critical dimensionless shear stress value of as low as 0.006 (compared to 0.06 from the Shields diagram) for relative protrusion = 0.94, the authors conclude that the effect of α decreases with decreasing protrusion due to the saltation mode of transport becoming dominant at higher flows.

Figure 2.12 The roll, lift and total entrainment probabilities expressed as a function of the dimensionless shear stress, and comparison with other studies (Reproduced from Wu and Chou 2003)

2.3.5 Discrete Particle Modeling

Discrete Particle Modeling (DPM) has also been used in sediment entrainment models to calculate the pick-up probability. McEwan and Heald (2001) uses DPM to numerically model a random non-waterworked uniform sized sediment bed to account for direct and remote sheltering effects; and apply drag forces based on grain stability to obtain the probability distribution of the critical shear stress. The cumulative distribution for the different sizes of sediment used without considering sheltering effect can be seen in Figure 2.13, and distributions evaluated with sheltering effects are shown in Figure 2.14. Figure 2.13 reveals that the Shields dimensionless shear stress value of 0.06 corresponds to a mobile fraction of 1.4% by weight of the surface grains. This compares with Cheng and Chiew's (1998) model in which they obtain a mobile fraction of 2% of the total number of grains in a

given area on the bed for the same stress value. DPM has also been used for modeling mixed sized sediment bed in McEwan et al. (1999).

Figure 2.13 Cumulative distribution of entrainment for sediment sizes of 2 mm, 4 mm and 8 mm with no sheltering effects considered, where τ_{crg} refers to the critical entrainment shear stress of a single grain (Reproduced from McEwan and Heald, 2001)

Figure 2.14 Distributions of entrainment (approximately lognormal) for no sheltering, direct sheltering and remote sheltering (Reproduced from McEwan and Heald, 2001)

2.3.6 Concept of 'critical impulse' for sediment entrainment

In studies discussed in the above sections, some of the researchers adopted a critical bed shear stress condition to delineate entrainment and no-entrainment, whereas others used a critical instantaneous force (drag force, F_D and lift force, F_L). In similar fashion, studies by Celik et al. (2010), Valyrakis et al. (2010), Celik et al. (2013), Diplas and Dancey (2013), etc. proposed a 'critical impulse' concept where in addition to the force magnitude, the duration of the force is given due consideration too. The authors simulate the fluctuating turbulent forces as short-lived pulses which transfer the critical impulse to the sediment particle leading to its entrainment. They validate their theoretical model with experimental results, and conclude that high magnitude hydrodynamic forces can cause entrainment only when they last for a sufficiently long duration, thus providing an impulse higher than the critical impulse. Fig. 2.15 exhibits such a critical impulse scenario, where occurrence of sediment movement and occurrence of a sufficiently high impulse is seen to take place at the same time.

They also extend their concept by using direct pressure measurements on a fixed particle to calculate the impulse (Celik et al., 2014) rather than using the velocity time series as is done in Fig. 2.15. Here, too, they obtain similar results as in their previous studies, and also find impulse events to be well represented by a lognormal distribution or any similar long tailed distribution.

Figure 2.15 Time series of V_x^2 , impulse and target grain movement (Reproduced from Celik et al., 2010)

2.4 Recent experimental studies on sediment entrainment

Besides numerical probabilistic methods being applied to model sediment entrainment, studies have also experimentally investigated the role of coherent structures, turbulence bursting and large-scale eddies in sediment motion (Sumer and Deigaard, 1981; Rashidi et al., 1990; Ninto and Garcia, 1996).

2.4.1 Role of coherent flow structures in sediment entrainment

Wu and Shih (2012) have conducted Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) measurements to better understand the role of vortices in moving a sediment particle from its at-rest position. The authors contend that even with weak flow velocities, the pressure associated with coherent structures is large enough to entrain a sediment particle. Their experiments show that retrograde vortices (spanwise vortex rotating counter to mean shear) are mostly responsible for the phenomenon. Quadrant analysis of their experiment reveals that pre-entrainment, Q1 outward-interactions witness a spiky rise with a mild rise for Q4 sweeps, which is followed by a dominating Q4 and declining Q1 post-entrainment, evidence of a retrograde vortex causing a particle to entrain (Figs. 2.16, 2.17).

Figure 2.16 Retrograde vortex entraining (a) an exposed particle, and (b) a sheltered particle (Reproduced from Wu and Shih, 2012)

**Figure 2.17 Pre- and post-entrainment cumulative quadrant fractions versus shifted time
(Reproduced from Wu and Shih, 2012)**

Dwivedi et al. (2010) have also studied the effect of coherent structures and hydrodynamic forces on a sediment particle entrained from a flume recess. The recess of 0.26 m depth and 0.90 m length has three rows of 39.7 mm diameter balls, topped by a group of balls 1 diameter height, followed by the target particle with diameter = 38.3 mm at the topmost position. The rest of the flume is also covered with one layer of the same balls for a length of 5.5 m in a 11.8 m long flume (Fig. 2.18). The experiment involved pressure measurements on the fixed target particle and recording of flow structures during entrainment using a movable target particle. The number of runs for each particle protrusion ($e = 11$ mm, 17 mm) are 4 and entrainment is made to occur once every 2 minutes by adjusting the flume slope, pump speed and overflow water level. Figure 2.19 and Figure 2.20 show the time histories and contours of measured parameters respectively for a particular experimental run.

Figure 2.18
Hydrodynamic forces on a spherical sediment particle as viewed from the side of the flume (Reproduced from Dwivedi et al., 2010)

Figure 2.19 Time histories of instantaneous streamwise (V_x) and vertical velocities (V_y), pressure fluctuations at target particle bottom (p'_4) and particle protrusion (e) during entrainment (Reproduced from Dwivedi et al., 2010)

Figure 2.20 Contours of V'_x , V'_y and vector plots of V'_x , V'_y at entrainment (Reproduced from Dwivedi et al., 2010)

Quadrant analyses of the time histories based on the signs of V'_x and V'_y show the Q4 sweep event to have a higher probability of occurrence and a major contributor to sediment entrainment (Fig. 2.21). Q4 sweeps are followed by Q2 events in their order of contribution, while Q1 and Q3 are seen to have little importance in the entrainment process. The results can be compared to that of Wu and Shih's (2012) model which gives the same quadrant fractions for the post-entrainment scenario as seen in Figure 2.17.

Figure 2.21 Probability density of drag force in: (a) normal scale, (b) log scale for $e = 17$ mm; and lift force in: (c) normal scale, and (d) log scale for $e = 11$ mm based on quadrant analysis (Reproduced from Dwivedi et al., 2010)

In addition to the quadrant analysis discussed in the above studies, researchers have also gone ahead with generalizing the conventional 2-dimensional quadrant analysis to a 3-dimensional octant analysis using the streamwise, vertical and spanwise velocities (Keshavarzi et al., 2014; Keylock et al., 2014). Keylock et al. (2014) have characterized the flow structures responsible for sediment entrainment using conditional probability of occurrences of the 3-dimensional octant sequences having maximum contribution to the total shear stress. So instead of a particular octant event being solely responsible for

entrainment, they show that it is the sequence of occurrence of different octant events that is more important to consider for particle entrainment. Similarly, Keshavarzi et al. (2014) have conducted octant analysis of the 3-dimensional flow structures around a circular bridge pier to calculate the transition probabilities of the bursting events. They find external sweeps (Q4 events with $-V_z'$) and internal ejections (Q2 events with $-V_z'$) to have the highest transition probabilities with maximum contributions to sediment entrainment around the pier.

2.4.2 Role of large scale flow structures in sediment entrainment

The existence of flow structures ranging from the micro-scale (turbulence dissipative scale) to the macro-scale (geomorphological bed forms) is already well-established (Nikora, 2008). Some of the studies involved in observing these large-scale (LS) eddies in turbulent open channel flows in laboratory experiments are Shvidchenko and Pender (2001), Fox and Patrick (2008), Silva and Ahmari (2009), Roussinova et al. (2010) amongst others. These studies report LS flow structures with sizes comparable to the flow depth (h), and in some cases, the streamwise length scale of the eddies are found to be several times the flow depth (h), thus occupying a large area of the flow regime. Methods used in these studies to detect the presence of the LS flow structures vary from the simple moving-average smoothing method to triple decomposition (dividing the velocity time series into a mean component, a fast frequency fluctuation and a slow frequency fluctuation) to the more advanced inhomogeneous decomposition - Proper Orthogonal Decomposition (POD).

Shvidchenko and Pender (2001) have also studied the effect of these LS eddies on sediment entrainment from flat beds. They attribute entrainment to the up and down movement of the fluid due to the eddy motion exerting drag and lift forces on the bed particles in a cyclical manner. The sediment bed in their study also exhibits the formation of longitudinal sediment ridges and troughs, highlighting the path and size of the eddy motion, as can be seen in Fig. 2.22.

In addition to these studies on laboratory scale, large scale flow pulsations and their effect on sediment entrainment have also been investigated through field measurements in rivers by Marquis and Roy (2011, 2013). Their studies conclude that quadrant events are primarily

considered responsible for sediment entrainment, i.e. ejections and sweeps, are embedded within larger flow scales in a self-similar manner, which in turn, are dependent on the river bed morphology.

Figure 2.22 Model of three-dimensional large-scale turbulent structure of open-channel flow over a mobile bed (Reproduced from Shvidchenko and Pender, 2001)

Large scale flow structures are also observed in a rectangular cavity of $L/D = 2 - 4$ in Ashcroft and Zhang (2005). The authors decompose the velocity field into large-scale and small-scale flow structures using the Galilean decomposition and Large Eddy Simulation (LES) decomposition approach. The shear layer is seen to be characterized by flow structures whose size and rate of growth vary with the cavity geometry. These structures are seen growing in size and convecting downstream until the cavity trailing edge impedes its further development.

2.4.3 Sumer et al.'s (2001) study on suction removal of sediment

Sumer et al. (2001) have experimentally investigated the removal of sediment from between armor blocks and attribute the cause to the formation of local vortices. The authors differentiate their study of suction removal and incipient motion by considering the certainty of transport in the former and the uncertainty in the latter which may involve sliding, rolling or lifting without any subsequent removal of the sediment from the cavity. However, the

study comes out with a diagram delineating regions of suction and no-suction based on an empirical critical shear stress equation, similar to Shields' critical stress diagram for incipient motion, thus treating the phenomenon as a deterministic one. The time duration of 2 minutes for observing the critical condition in single particle experiments is arrived at by using the following relation between the mean-bursting period, flow depth and flow velocity (Nezu and Nakagawa, 1993, p. 190):

$$\frac{\overline{T_B} V_{x,max}}{h} \approx \frac{\overline{T_e} V_{x,max}}{h} \approx \frac{\overline{T_s} V_{x,max}}{h} = 1.5 - 3.0 \quad (2.16)$$

where $\overline{T_B}$, $\overline{T_e}$, $\overline{T_s}$, $V_{x,max}$ and h represents mean-bursting period, ejection period, sweep period, maximum streamwise flow velocity and flow depth respectively. However, the authors use O(5) instead of 1.5-3.0 on the right hand side of the above equation. The suction removal is attributed to the penetration of a single vortex in the cavity made evident by visual recordings, and turbulence quantities reaching their maximum at the cavity centre. Moreover, the removal mechanism is said to be the same for all velocities ranging from 38 cm/s to 71.4 cm/s. The plot of critical Shields parameter as a function of single particle size (d) / mean stone size (D_s) is shown in Figure 2.23, which divides the plot into three sections namely: no-motion, motion-without-suction, and motion-with-suction regions. They also surmise that the stone shape is not a significant factor as all the curves with different shapes collapse into a single representative curve. The authors also contend that the stone Reynolds number is not as significant because of the experiment's high value of stone Re_{st} varying from 45-15,000, thus making the bed a fully rough boundary.

The empirical equation relating the critical Shields stress for suction onset ($\tau_{cr-sumer}^*$) and d/D_s ; and the timescale (T) equation for suction of sediment and resulting downward displacement of the stones (Δ) are given as:

$$\tau_{cr-sumer}^* = 0.3 + 3 \left(\frac{d}{D_s} \right)^{-0.15} \exp \left(-7.5 \frac{d}{D_s} \right) \quad (2.17)$$

$$\Delta = \Delta_0 \left[1 - \exp \left(-\frac{t}{T} \right) \right] \quad (2.18)$$

where Δ_o and t are the equilibrium level of Δ and time respectively.

Figure 2.23 Plot of critical Shields parameter as a function of d/D (d replaces d_{50} in case of sediment bed) (Reproduced from Sumer et al. 2001)

The above study is followed by another similar experimental investigation (Dixen et al., 2008) that takes into account the effect of waves on the same phenomenon studied in Sumer et al. (2001). The critical parameter used in the study is the mobility number expressed as a

function of stone diameter to flow depth ratio, and the Keulegan-Carpenter number. This work is again succeeded by another study investigating the same phenomenon under the effect of breaking waves on a beach (Nielsen et al., 2012) using the critical sediment mobility number as a function of the stone diameter to flow depth ratio, and the surf similarity parameter. The follow-up studies use irregular stone armor blocks as well as regularly placed cubical concrete blocks for studying the entrainment or 'suction' removal of sediment in between them. Although the sediment removal in Nielsen et al. (2012) is attributed to turbulent diffusion and descending eddies, the complex mechanism is not articulated in clear terms in the study.

2.4.4 Sediment entrainment from grade control structures

Complementing the above studies on sediment entrainment, removal of large sized stones in between stepped concrete block grade control structures has been investigated by Lai et al. (2010). The authors conduct their experiment in a 1:50 scaled physical model of a control grade structure (see Fig. 2.24 (a)), and report their findings on the scour features and the migration process of the eroded stones.

The authors report that the scour depth is not directly proportional to the approach discharge, and observe higher gap scour at low and moderate discharge rather than at high discharge. It is seen from the experiments that entrainment of eroded stones from between the gaps occur as bed-load instead of suspended load, with the stone mobility behavior similar to bed load transport dominated by gap flows. A decrease of 98.7% in the maximum scour depth is observed with sealed longitudinal gaps between the blocks. The bed profiles in the armor structure can be seen in Figure 2.24 (b). Based upon their findings on gap scour values and its mechanism, the authors propose a new design methodology and prescribe appropriate block heights to reduce the damage caused to the control grade structure as a consequence of the scouring process.

Fig. 2.24 (a) Sketch of scaled physical model (side and plan view) (Reproduced from Lai et al., 2010)

Figure 2.24 (b) Mean bed-form profile in gaps between armor blocks (Reproduced from Lai et al., 2010)

However, it should be noted that in this experiment, the main flow passes through the blocks and gaps instead of just dropping over the gaps as is done in Sumer et al. (2001) or in studies on vertical drop pools or cavities which will be discussed in Section 2.5.

2.5 Experimental studies on cavity flows

Numerous experimental studies (Lin et al., 2004; Lin et al., 2008; Haigermoser et al., 2009; Lin et al., 2009; Mori and Naganuma, 2009; Cicca et al., 2013; Fernando et al., 2013; etc.) have also been conducted to characterize flows in cavities or over vertical drop pools without involving the process of sediment entrainment. Such studies which focus solely on the flow characterization are noteworthy, because coupling these studies with the sediment transport phenomenon can help explain particle entrainment from a cavity, by examining the formation and dissipation of recirculation bubbles, shear layers and turbulent structures, etc. inside the cavity.

2.5.1 Flow over a vertical drop pool

Lin et al. (2004) have experimentally studied the flow over an infinite length free overfall under varying velocity and flow depth. Flow visualizations from their study show chaotic turbulence in the pool, with primary circulation partially occupying the pool length and a secondary cell of less organized circulation near the corner of the vertical drop. The circulation in the pool is also confirmed from vertical distributions of velocity profiles showing negative velocity at the pool bottom and positive values near the top (Fig. 2.25). Large velocity gradient between the sliding jet and the pool forms a structure similar to a shear-layer, creating a large entrainment effect. Gravity is seen to affect the maximum jet mean velocity more than the upstream water depth. The study also confirms that the ratio of critical upstream flow depth to the vertical drop height is an important parameter for describing the flow characteristics.

Figure 2.25 Definition sketch of the deflected wall jet (Reproduced from Lin et al., 2004)

Lin et al.'s (2008) study explores the periodic oscillatory flow over a finite length vertical drop with an end sill. Here, end sill refers to the downstream edge of the pool whose height is generally lower than the upstream edge drop height. Flow visualizations show the formation of a jet that switches between an impinging jet of a napped flow and a surface sliding jet of a skimming flow periodically, with a unique period. The switching involves repeated growth and decay of two vortical structures in the pool. This periodic oscillation may hold clue to particle movements inside a cavity until its final entrainment. The authors express the primary frequency of oscillation (f_o) by a relationship between the weighted the weighted Strouhal number (S'_t) and a grouped parameter (π_x) as follows:

$$S'_t = 0.0095 \ln(\pi_x) + 0.103; \text{ where } S'_t = \frac{f_o \Delta h}{V_{x,c}} \text{ and } \pi_x = \frac{h_{vd}^{3.5} \Delta h V_{x,c}^5}{g^{2.5} L_p^7} \quad (2.19)$$

where Δh , $V_{x,c}$, h_{vd} , g and L_p are the difference between vertical drop height and end sill height, critical approach flow velocity, vertical drop height, acceleration due to gravity and length of the pool, respectively. The authors also provide a plot delineating the region of possible occurrence of periodic oscillation, that separates the napped from the skimming

flow (Fig. 2.26), which can prove to be effective in explaining oscillatory or periodic particle movements in the cavity as flow parameters are varied.

Figure 2.26 Region of possible occurrence of periodic oscillation (confined by the dotted lines and the dashed lines) (Reproduced from Lin et al., 2008)

The shear layer in skimming flows has been investigated by Lin et al. (2009) over a finite length vertical drop pool under varying flow rates and ratio of vertical drop height (h_{vd}) to end sill height (h_s). A distinguishing feature of this study from the two studies mentioned above (Lin et al., 2004, 2008) is that it includes flow measurements for cavity flows with $h_{vd}/h_s = 1.0$. Plots of turbulent intensities show Reynolds shear stress (lower x-axis in Fig. 2.27) to dominate over viscous shear stress (upper x-axis in Fig. 2.27) during the mixing process along the shear layer between the sliding jet flow and the pool. In the figure, s_1 and s_2 refers to the coordinate along the upper surface of the sliding jet, and the coordinate outward normal to the free surface of the sliding jet, respectively. Moreover, eddy viscosity is seen to increase with increase in the sliding jet's arc length (s_1), resulting in a larger Reynolds shear stress downstream of the shear layer.

Figure 2.27 Profiles of Reynolds shear stress and viscous shear stress in the shear layer region for the cavity flow case $H:h=1.0$ (Reproduced from Lin et al. 2009)

2.5.2 Laminar and turbulent flows over a deep rectangular cavity

The flow in a rectangular cavity has also been experimentally investigated for its 3-dimensional features with PIV recordings in both the XY and XZ planes (X, Y, and Z being the streamwise, vertical and spanwise directions of the flow, respectively). Cicca et al. (2013) have studied the 3D flow features in a rectangular cavity of $L/D = 3$ (length (L) = 3 cm, width (W) = 35 cm, depth (D) = 1 cm) with a laminar incoming boundary layer ($Re = 9300$) in a water tunnel. Results from the vertical XY plane images show a primary and secondary recirculation vortex near the cavity downstream and upstream edges respectively, with higher fluctuations in the downstream bubble zone and shear layer (Fig. 2.28). The XY plane PIV results also show vortices arising from Kelvin-Helmholtz (KH) instabilities and causing shear layer oscillations. The vortex shedding frequency is observed to be 10 Hz which is the same as that of self-sustained shear layer oscillations at a Strouhal number = 1.0.

Figure 2.28 Normalized mean velocity modulus and sectional streamline patterns, where u_e is the external undisturbed flow velocity (Reproduced from Cicca et al., 2013)

Fig. 2.29 shows the XZ plane images just above and below the cavity, depicting extensive differences between the two planes. The flow in the latter plane is seen to be directed towards the mid-plane and the cavity leading and trailing edges, dividing the entire plane into four different flow quadrants. The XZ plane images also reveal irregular velocities in the spanwise direction causing spiral recirculation bubbles, with the 2D coherence of the velocity zone breaking up as it moves downstream (Fig. 2.30). This loss of spanwise coherence in the flow structures is attributed to flow ejection from the cavity by the recirculation bubble and transportation of small vortices into the shear layer.

Fig. 2.30 shows the 3D tomographic PIV images giving a more detailed picture of the flow structures than conventional planar PIV. 2D PIV images showing the appearance and disappearance of vortices cannot be interpreted as vortex formation and dissipation because of the images being recorded in a particular plane of the flow field. This is because the vortices may in reality be evolving or moving over to other planes. In scenarios of complicated flow structures with vortex interactions, 3D tomography with a bigger measurement volume can be of significant help in the understanding of the flow field (Scarano, 2013).

Figure 2.29 Streamwise component of mean velocity and streamlines at $y = +0.05D$ (left) and $y = -0.4D$ (right). (Reproduced from Cicca et al., 2013)

Figure 2.30 XZ slice through velocity vector field at $y = -0.3D$, $L/D = 3$ showing 2D coherent flow structures breaking up downstream. (3D tomographic PIV images in Haigermoser, 2009: Reproduced from Cicca et al., 2013)

Experiments similar to Cicca et al. (2013) have also been carried out by Haigermoser et al. (2008) albeit in a turbulent incoming boundary layer ($Re = 18500$) under low Mach number with a rectangular cavity of $L/D = 4$ (depth = 1 cm) in a water tunnel. However, no self-sustained oscillations are reported due to a low $L/\Omega = 18 \ll 80$ with Ω being the

momentum thickness, in accordance with Gharib and Roshko (1987). A bigger recirculation bubble with its center farther from the trailing cavity edge, compared to the laminar case of Cicca et al. (2013) is seen in the XY plane. This upstream movement of the centers of the primary and secondary vortices with increasing Reynolds number is also observed in wind tunnel experiments by Ozsoy et al. (2005) for a cavity of $L/D = 4$ with $Re = 16000-52000$. From the drag power spectrum's peak of 2 Hz at Strouhal number = 0.2, which is 5 times lower than the vortex shedding frequency of 10 Hz, Haigermoser et al. (2008) conclude that the shear layer oscillations are not due to vortex shedding as is the case in the laminar flow of Cicca et al. (2013). Instead, the oscillations seem to arise from the coupling of pseudo-streamwise hairpin shaped structures in the boundary layer and quasi-spanwise aligned vortices due to shear layer instabilities, along with fluid ejection from the recirculation zone. However, the mean flow characteristics with turbulent boundary layer seem to match with those of the laminar boundary layer. Although the XZ plane PIV images within the cavity are not provided, Faure et al. (2009) has reported the absence of 3D flow structures at low Re due to low advection velocity and also at high Re (such as in Haigermoser et al., 2008) due to high turbulence effects.

Turbulent boundary layer experiments by Mori and Naganuma (2009) with $L/D = 1-4$ (length = 4 cm, 8 cm, 16 cm) and $Re = 200,000-800,000$ also report no resonance or self-sustained oscillations. This may be attributed to the high turbulence as seen in Haigermoser et al. (2008), or the lack of coherent structures as reported in Faure et al. (2009) for high Re . The frequency peak from surface pressure spectra is also close to the unstable frequency of the shear layer, leading to weak interaction between the shear layer and the cavity, and thus inhibiting any resonance behavior. This shows that the shear layer plays a significant role in the cavity oscillations even for highly turbulent flow.

Fernando et al. (2013) have also studied the vortex structures in a rectangular cavity of $L/D = 2$ at $Re = 60000$ in a free surface water tunnel with a PIV analysis in both the XY and XZ planes. The first four modes from the modal analysis on the vertical XY planes are shown in Figure 2.31; with the modes representing the shifted flow pattern, shear layer fluctuations, fluctuating strength and vortex meandering respectively. The authors report the first shift

mode in the XY plane being responsible for the spanwise incoherence observed in a rectangular cavity flow, and the reduced spanwise coherence being the result of interaction with the side walls forming vortices in the backflow region.

The 3-dimensional turbulence structure in the side-cavity of an open channel flow studied in Sanjou et al. (2012) with special emphasis on momentum exchange also shows shear instability from velocity difference between the mainstream and embayment flow resulting in small scale vortex shedding.

Figure 2.31 First four common-base modes for the rectangular cavity (Reproduced from Fernando et al., 2013)

2.5.3 Studies of flow in a shallow rectangular cavity

Section 2.5.2 covered studies done in deep rectangular cavities where the aspect ratio (L/D) generally ranged between 1 - 4. Recently, studies have also been conducted in shallow rectangular cavities with $L/D \geq 10$. Some of these studies are Esteve et al. (2000), Reulet et al. (2002), Zidanski et al. (2000), Madi Arous et al. (2011), amongst others. Esteve et al. (2000) has studied the flow field in a cavity ($L/D = 10$) inside a wind tunnel under low Reynolds number (38000, and 64000 based on cavity depth). The flow visualizations exhibit

a primary vortex covering around 65% of the cavity length, and a small secondary vortex near the cavity downstream edge as shown in Fig. 2.32. In addition to the recirculation vortices, a stagnation zone and a thin sub-layer of less than 2 mm thickness is also observed near the cavity floor. This sub-layer with negative streamwise velocity is seen to stop the reattachment of the shear layer to the cavity bed. Reulet et al. (2002), which is an extension of the work done by Esteve et al. (2000), investigated the interaction of coherent structures with the cavity bottom wall using PIV, and observed these structures destroy the boundary layer during the interaction.

Fig. 2.32 Turbulence intensity and streamlines for $L/D = 10$ (Reproduced from Esteve et al., 2000)

Zidanski et al. (2000) have conducted numerical simulations of laminar flow over a shallow rectangular cavity in a wind tunnel to investigate the influence of Reynolds number on the cavity flow field characteristics. They find that the Reynolds number affects not only the recirculation vortex's location but also the shape (please refer Fig. 2.33). With increase in Reynolds number, the bubble centers are seen to move closer to each other.

Sections 2.5.2 and 2.5.3 thus show that different cavity configurations lead to vastly different cavity flow field features and when combined with the small scale randomness already present in any turbulent flow, particle entrainment can be affected significantly and in a myriad of ways.

Fig. 2.33 Flow topology showing changing shape and position of recirculation vortices inside the cavity ($L/D = 12$) with change in Reynolds number (a) $Re = 147$ (b) $Re = 662$ (Reproduced from Zidanski et al., 2000)

2.6 Concluding Remarks

The above literature review clearly shows that the phenomenon of sediment entrainment has already moved into the stochastic field from its modest beginnings in the deterministic arena, as discussed in Sections 2.2 and 2.3. Probabilistic studies have tried to incorporate the randomness in the phenomenon by making use of various probability distributions in their model for the parameters influencing sediment motion, ranging from flow parameters to sediment properties and bed features. However, as seen in Section 2.4.2, Sumer et al.'s (2001) experimental study on suction removal of sediment between armor blocks relies heavily on a deterministic model with the emphasis of putting forward a critical or threshold shear stress for sediment motion and suction (Fig. 2.23). Considering the fact that such sediment entrainment can cause failure of massive control grade structures, focus has to be

moved towards modeling this extreme phenomenon more accurately using probabilistic approaches.

It is also observed from the literature reviewed that although many studies have focused on sediment entrainment using a probabilistic approach, these are all restricted to flat beds with the exception of Sumer et al. (2001) and Lai et al. (2010). Additionally, studies on rectangular cavities (covered in section 2.5.2 and 2.5.3) have focused on the cavity flow field physics alone without investigating its effect on particle entrainment from the cavity. Integrating these two approaches will enable researchers to calculate entrainment probabilities, as well as predicting particle trajectories based on a fundamental understanding of the flow mechanisms inside the cavity.

Thus, there is an urgent need to undertake extensive and sufficiently detailed experiments which can integrate the stochastic nature of sediment entrainment with the cavity flow physics, in order to accurately and effectively predict the sediment removal probabilities from armored beds. To meet this objective, experiments need to be conducted by varying all the parameters associated with the entrainment phenomenon such as particle density and size, flow and shear velocity, cavity dimensions, etc. Flow visualization also need to be done along different planes inside the cavity so as to capture the entire particle removal mechanism, and explain it in terms of the flow characteristics prevailing in the cavity. The description and results of these experiments will be the content of succeeding chapters.

Chapter 3

Experimental setup & measurement techniques

3.1 Introduction

This chapter describes the different experimental set-ups and methodologies employed in the present study. In broad terms, the experiments are conducted in the following two phases:

1. In the first phase of the study, experiments are performed to determine the entrainment probability of different particles under different series – Series 1: varying cavity depth (D); Series 2: varying free-stream flow velocity (u); and Series 3: varying cavity length (L). The flow measurements in these experiments are conducted only in the free-stream region using Acoustic Doppler Velocity Profiler (ADVP) and Acoustic Doppler Velocimeter (ADV). Here, entrainment refers to the escape of a particle from the cavity and not just its movement from its release position; and free-stream region refers to the region outside of the cavity.
2. In the second phase, the flow field is measured using Particle Image Velocimetry (PIV) both in the free-stream region and inside the cavity for the same test conditions as in Series 1 – 3. The flow profile obtained in the free-stream region using PIV is then compared with that obtained previously with the ADVP/ADV in Phase 1 experiments. This is done to make sure that the earlier flow conditions are replicated during these PIV recordings.

It is to be noted that in Series 1, only D is varied and the rest of the experimental parameters are kept constant. Similarly, in Series 2 and 3, only u and L is varied respectively, while the other parameters remain unchanged. The experimental set-up used in both phase 1 and 2 will be discussed in details here, along with the methods used in processing the experimental raw data so obtained.

3.2 Phase 1 experiments

3.2.1 Experimental set-up and instrumentation

The experiments are carried out in an open channel water flume that is 0.49 m wide, 0.6 m deep and 14 m long, with side walls made up of glass, and a steel bed. The flume consists of a 1 m long x 0.49 m wide rectangular cavity with opaque walls, and its upstream (or leading) edge is located 9 m downstream of the flume inlet. The cavity bed is made up of an aluminum plate which is attached to vertical rods, which in turn are connected to a piston and motor arrangement. This setup enables adjustment of the cavity depth (D) with a precision of ± 1 mm. The flume set-up, together with the instrumentation used - ADVP/ADV and a low-speed video camera, is shown in Fig. 3.1.

Figure 3.1 Schematic diagram of experimental set-up in Phase 1 (not to scale; all units in meters).

The particle was placed at the cavity center by using a sufficiently long, slender hollow pipe (dimensions: internal diameter = 1.5 cm, external diameter = 1.9 cm, length = 40 cm) made up of plastic (PVC) material. The pipe was held vertically with the pipe base touching the cavity bed and the pipe top opening used for dropping the particle in the pipe. When the

particle reached the cavity bed, the pipe was slowly removed from the water so as not to disturb the flow. This process was again repeated for the next trial and so on.

Steady uniform flow is achieved in the re-circulating flume with the help of a slope adjustable flume bed and honeycomb grid elements located at the flume entrance. Sponge meshes are also placed at the entrance of the flume to dampen the turbulence in the inlet head box, ensuring a stable uniform flow throughout the flume. The flume bed is roughened with sand of median grain size, $d_{50} = 0.36$ mm throughout the flume length except for the cavity bed. The former is to ensure a hydraulically rough surface and a fully developed flow in the free-stream region; and the latter is to make sure that entrainment and trajectories of small-sized and light weight particles in the cavity are not affected by sand particles for different low discharge conditions.

The entrainment experiments are conducted using six different particles, and their physical properties, namely diameter (d), density (ρ_s), and mass (m) are listed in Table 3.1.

Table 3.1 Physical properties of particles used in the experiments

Particle Type	Diameter $d \times 10^{-2}$ (m)	Density ρ_s $\times 10^{-3}$ (kg/m ³)	Mass $m \times 10^{-3}$ (kg)
SP1	2.35	1.01	6.86
SP2	1.38	1.03	1.42
SP3	0.62	1.10	0.14
SP4	0.60	1.11	0.13
SP5	0.78	1.10	0.27
SP6	0.63	1.20	0.16

The 3 test series conducted in Phase 1 experiments are briefly described below:

1. In Series 1, the cavity depth (D) is varied from 1 cm - 11.3 cm by moving the cavity bed up and down with the help of the piston arrangement. The cavity length is fixed at $L = 100$ cm, and all test runs in this series are conducted under the same free-stream flow conditions where the depth averaged streamwise velocity (u) is 26

cm/s, and the flow depth (h) is 12 cm. Here, u is measured 1 m upstream of the cavity leading edge,

2. In Series 2, the cavity configuration is kept constant ($L = 100$ cm, $D = 5.3$ cm) while the flow discharge is varied using the flume recirculation pump. The range of u is 7.8 cm/s - 38.5 cm/s and h is kept constant at 12 cm. To ensure the same flow depth (h) throughout all the test runs in this series, the bed slope (S_b) is varied from 0.2×10^{-4} - 3.7×10^{-4} as per the flow discharge used.
3. In Series 3, the cavity depth (D) and free-stream flow conditions are kept intact at $D = 5$ cm, $u = 26$ cm/s and $h = 12$ cm. The cavity length (L) is varied from 44.3 cm - 94.5 cm by placing a polyvinyl chloride (PVC) block of different lengths (equal to 100 cm - desired L) in the cavity to reduce the original cavity length to the desired L .

Furthermore, the detailed table of the experiment parameters and results for each test Series 1 – 3 are provided in the respective chapters 4 – 6 (Tables 4.1 - 4.3, 5.1 - 5.3 and 6.1) where the parameters are discussed along with their effect on particle entrainment probability (p) and on the cavity flow field characteristics. This is done so as not to repeat listing the same tables in different chapters throughout the thesis.

3.2.2 Free-stream flow measurements using ADVP/ADV

For all the test series from 1 - 3, the flow velocity profile is measured 1 m upstream of the leading cavity edge, which is 8 m downstream of the flume inlet. This measurement section ensures that the flow has fully developed by the time it reaches this location and is also not influenced by the presence of the cavity downstream of it. The velocity profile is collected using a down-looking Acoustic Doppler Velocity Profiler (Nortek's Vectrino II - ADVP) and a side-looking Acoustic Doppler Velocimeter (Nortek's Vectrino - ADV). The instruments utilize the Doppler shift to measure instantaneous velocities in the streamwise (x), vertical (y), and spanwise (z) directions. For these velocity measurements, the flow is seeded using a micro-hydrogen bubble generator situated 1 m upstream of the velocity profiler; an arrangement similar to that in Blanckaert and Lemmin (2006). In all the tests in Series 1 – 3,

the flow depth (h) outside the cavity is maintained at a constant value of 0.12 m, whereas the flow depth at the cavity, $H = D + h$ varies with the cavity depth (D).

The side-looking ADV is used in conjunction with the down-looking ADVP due to the latter's limitation of not being able to measure velocities for the top 5 cm below the free surface. Accordingly, the velocity profile is recorded from $y = 0 - 7$ cm using the ADVP and the remaining water column using the ADV. In order to get a high signal-to-noise ratio (SNR) in the velocity measurements, the ADVP is used for collecting the velocity only at a single point of 5 cm below the probe, which is the instrument's sweet spot with maximum SNR. Additionally, instrument settings and configurations are kept identical for both the velocimeters to avoid mismatch in the measurements.

The velocity time series are recorded for 3 minutes at a sampling rate of 70 Hz, thus generating 12,600 velocity samples for each point in the velocity profile. The recorded time series is then de-spiked using the Phase Space Thresholding (PST) method in Goring and Nikora (2002) and implemented in the software - Velocity Signal Analyzer (VSA) by Jesson et al. (2013). The filtered time series is then used for plotting the velocity profile, fitting the standard logarithmic law of the wall, and finally computing the approach shear velocity (u_*) from the fitted equation.

3.2.3 Particle entrainment probability calculations

The entrainment process is studied by first placing a particle at the center of the cavity bed, and observing it for a duration of $t_o = 2$ minutes to check if it escapes from the cavity or not. Furthermore, the entrainment time, t_e , i.e. the time at which the particle actually leaves the cavity is also noted. This entrainment of the particle from the cavity at $t_e \leq t_o$ is considered a success, and no entrainment is equated to failure. This process is repeated 50 times for each particle under the same test conditions, and the number of successes is noted. Taking the ratio of successful entrainments to the total number of trials gives the entrainment probability (p) under the specified test conditions in an operational sense - an

operational entrainment probability. This entire process is repeated for different particles at different test parameters corresponding to those in Series 1 - 3.

3.2.3.1 Observation duration

The 2 minute observation duration is referred from Sumer et al. (2001), Dwivedi et al. (2010), and formula from Nezu and Nakagawa (1993). From the equation proposed by Nezu and Nakagawa (1993), the macro-scale of turbulence (T_t) is calculated and 2 minutes is found to be very large compared to T_t , hence 2 minutes is used as the observation duration for all the trials. To be doubly sure, the observation duration is also compared to the grain scale of all the six particles, and is found to be very low compared to 2 minutes. Hence, $t_o = 2$ minutes is very high when compared with T_t (dependent on flow characteristics), and also very high compared to the grain scale (dependent on the particle characteristics). This observation duration of 2 minutes is hence considered justified for arriving at a value of the operational entrainment probability. However, observation durations in excess of 2 minutes, stretching to as long as 10 minutes are also considered in several test runs, with the aim of getting the complete timescale of the entrainment process.

Comparison of t_o with macro-scale of turbulence (T_t): As per As per Nezu and Nakagawa (1993), the macro-scale of turbulence, T_t such that a particle can experience an entire cycle of turbulence bursting – sweeps, ejections and interactions is given by $T_t = (h/u_{max})(1.5 - 3.0)$. Here, h is the flow depth and u_{max} is the maximum flow velocity. To compare this macro-scale of turbulence with the observation duration of 2 minutes, the maximum flow depth at the cavity which is 0.12 m (free-stream flow depth) + 0.113 m (maximum cavity depth used) = 0.233 m is taken. Furthermore, the lowest flow velocity = 0.078 m/s is taken, so as to get the upper limit of T_t . Thus, $\max T_t = (0.233/0.078)*3 = 8.96 \text{ sec} \approx 9 \text{ sec}$ which is very low compared to the 120 sec observation duration used in the study. Again, even if the characteristic length is taken as the cavity length instead of the total flow depth, still $T_t = (1/0.078)*3 = 38.46 \text{ sec}$ which is again very low compared to 120 sec.

Comparison of t_o with grain scale: Kuai et al. (2012) has demonstrated that bed-load or sediment motion time scale (or grain scale) is best represented by the ratio of water depth (h) to the settling velocity of the particle (v_t), i.e. h/v_t . Similarly, other particle time scales used by different researchers are d/v_t , d/u_* (Nino and Garcia, 1998) as particle saltating time scale, and L/v_t (Ancey et al., 2006). The first two ratios give very small timescales whereas the third one is dependent on the observation window length. Ancey et al. (2006) defined the sediment particle timescale as the typical travel time of moving particles across the observation window in their experiments. Thus, to compare with the experimental observation duration of 120 sec, the grain scales h/v_t and L/v_t are considered below, so as to get the upper limit of the grain scales. To get the maximum grain scale, h is again taken as the maximum flow depth at the cavity = 0.12 m (free-stream flow depth) + 0.113 m (maximum cavity depth) = 0.233 m. Also, L is taken as the entire cavity length of 1 m which is the ceiling for the length considered. This is to get the maximum grain scale possible and compare it with the observation duration of 2 minutes. The particle terminal velocity or settling velocity is calculated using the equation $v_t = \sqrt{4gd(s-1)/3C_D}$ where C_D is calculated from Cheng, 2009. The particle settling velocities and the grain scales are presented in Table 3.2.

Table 3.2 Particle settling velocities and grain scales

Particle Type	$v_t \times 10^{-2}$ (m/s)	h/v_t (s) ($h = 0.233m$)	L/v_t (s) ($L = 1m$)
SP1	8.6	2.71	11.6
SP2	11.4	2.04	8.8
SP3	13.4	1.74	7.5
SP4	13.8	1.69	7.2
SP5	15.4	1.51	6.5
SP6	19.6	1.19	5.1

Thus, from the grain scales so obtained in cols. 3 and 4 in the above table which are $\ll$ the observation duration of 120 sec, it can be said that the particle is definitely exposed to all

kinds of flow structures in the cavity flow field. Thus, interactions between flow and grain scales are considered in the entrainment observation duration and are hence incorporated in the entrainment results as well. This observation duration of 2 minutes is hence considered justified for arriving at a value of the operational entrainment probability.

3.2.4 Sensitivity of Entrainment Probability to Number of Trials

Since particle entrainment from the cavity within 2-minute duration is considered a success and no-entrainment is equated to failure, this model of successes and failures falls under the scope of a binomial distribution. Furthermore, probability values using the frequentist approach need to be labeled with an error margin at a reasonably acceptable confidence interval. The requirement of using a reasonable number of total trials to compute an entrainment probability brings us to the study of Krishnamoorthy and Peng (2007). Their work allows one to compute the number of maximum trials that is needed to get a probability value with a specified error margin and at a specified confidence interval. Their study shows that for a binomial distribution model, the maximum number of trials required for an error tolerance of ± 0.1 at 95% confidence interval, is 92 (Wilson-score method) or 103 (Clopper-Pearson exact method) for a probability value of 0.5. Hence, two preliminary experimental runs are conducted with 100 trials to test the sensitivity of entrainment probability (p) as a function of sample size. These entrainment probability sensitivity plots for two test runs from Series 1 are shown in Fig. 3.2 (a) and (b) with SP5 and SP6 particles at cavity depth, $D = 81$ mm and 53 mm, respectively. The entrainment probability is plotted with respect to a semilog x-axis (number of trials) to appreciate the convergence (Balio and Guadagnini, 2004). The figures show that entrainment probability reaches a constant value after $\approx 40 - 50$ trials. In the case of SP5, the variation in p for 50 and 100 trials is 0.02 whereas for SP6 this variation is 0.04, which are quite small and hence, acceptable. Hence, it can be safely concluded that using 50 trials in the present context is sufficient and reasonable to arrive at the entrainment probability, at least in an operational sense.

Figure 3.2 Entrainment probability (p) vs. number of trials: (a) SP5 particle at $D = 81$ mm; (b) SP6 particle at $D = 53$ mm.

3.2.5 Recording of particle trajectories in the XZ plane

The movement of particles in the streamwise and spanwise directions within the cavity is recorded with the low-speed video camera placed on top of the flume (please refer to Fig. 3.1). This recording, coupled with visual observations, enables presentation of a complete 3-

dimensional view of the entrainment process. The recorded video is processed using the particle tracking code developed by Hedrick (2008) to obtain the pixel coordinates of the moving particle, which are then scaled to the real physical particle coordinates inside the cavity. Hence, the entire particle motion from the moment it is released at the cavity center until its entrainment from the cavity is recorded, digitized and plotted as plan-view trajectories in chapter 4.

3.3 Phase 2 experiments

3.3.1 Experimental set-up and PIV instrumentation

As shown in Fig. 3.1, the cavity side walls are made up of an opaque material, causing PIV flow field measurements inside the cavity to be impossible. To address this limitation, a transparent false floor is installed in the flume and the original cavity bed is lifted to the level of the original flume bed (refer to Fig. 3.3 (a)). This newly made cavity has the false floor section beyond its upstream and downstream side, and transparent glass wall of the flume on the other two sides (sidewall) rather than the previous opaque steel sidewall. This modified set-up is then used for all the PIV measurements replicating the test runs in Series 1 - 3. A ramp section with slope 1:8 is also provided at the flume entrance to enable smooth transition of the flow from the head box over to the false floor top. The false floor is constructed using acrylic with wall thickness of 1 cm, and supported at regular intervals throughout the flume length. Thus, phase 2 set-up remains the same as in phase 1, with the only change that in the former, the original flume bed is raised by introduction of the false floor, which in turn enabled PIV measurements to be conducted inside the cavity.

PIV flow field measurements are carried out at different sections in the flume, along 4 streamwise planes (XY) and 1 spanwise plane (YZ). These different measurement planes are:

1. XY plane at 1 m upstream of the cavity leading edge in the free-stream region, along the flume centerline,
2. PL01 - XY plane near the cavity downstream edge along the flume center-line,

3. PL02 - XY plane parallel to PL01 near the cavity side wall at $z = 1$ cm,
4. PL03 - YZ plane parallel to the cavity downstream edge and 1 cm upstream of it, and
5. PL04 - XY plane at the cavity center along the flume center-line.

Figure 3.3 Schematic diagram of Phase 2 experimental set-up: (a) elevation; (b) magnified plan-view of the circled region in (a) (not to scale; all units in meters).

Thus among the streamwise XY planes, 1 is in the free-stream region and the other 3 are inside the cavity; the 1 spanwise plane is also inside the cavity. These different measurement planes along with the camera locations for PL04 and PL03 planes as seen in the plan-view are illustrated in Fig. 3.3 (b). It is to be noted that the PIV measurements at all these planes are done one at a time, and not simultaneously, and the camera and laser is moved depending on the plane in which the flow field is to be measured.

The arrangement of the PIV system is different for the streamwise planes and the spanwise plane as can be deduced from Fig. 3.3 (b). For the streamwise planes, the laser is kept at the flume top with the laser sheet pointing downwards in the flow, and the flow field is directly recorded by the hi-speed camera kept perpendicular to the laser sheet outside of the flume. For the spanwise plane, the laser is kept at the flume top too, but the plane is recorded indirectly from the laser sheet's reflection on the mirror (mirror location marked as 'M' in Fig. 3.3 (a)) which is kept below the false floor. This is done because in order to record from the laser sheet directly, the camera would have to be kept inside the water, which is not possible for the current camera used. As the cavity is between the false floor sections, and the mirror is kept below the false floor bed, the mirror cannot extend completely to the cavity top, as the false floor has a thickness of 1 cm. Hence, if the cavity depth is D , the spanwise flow field could be recorded to a maximum depth of $(D - 1)$ cm. The mirror could have been placed inside the cavity to record the flow as well, but this would have disturbed the flow and given erroneous results, and hence this arrangement was avoided.

In all the above cases, the laser light entered the water surface directly. No plate or streamlined window was placed on the free surface as water surface undulations were very low. This was also done to avoid any disturbance caused by the plate to the cavity flow field, especially to avoid affecting the growth or movement of the large scale flow structures. Also, the test section was far away from the flume inlet (8 m – 10 m) which ensured a smooth water surface near the measurement planes.

The light source in the PIV system consists of a 5 Watts Diode-Pumped Solid-State (DPSS) continuous laser with a wavelength of 532 nm corresponding to the visible green spectrum. An arrangement of mirrors and cylindrical lenses in the laser apparatus converts the laser

beam into a fan-shaped laser sheet of 1 mm thickness along the measurement sections. The flow is seeded with polyamide tracer particles of diameter = 20 μm and specific gravity = 1.23 for optimal scattering of the laser light.

The recording is done using a hi-speed CCD (charge-coupled device) monochrome digital camera (Phantom Miro M120) capable of recording a maximum of 1900 x 1200 pixel images at 730 frames per second (fps). However, due to its limited internal memory buffer of 3 GB (Gigabytes), the flow is recorded at lower frame rates up to a maximum of 200 fps, to rather record for a longer continuous duration at lower fps than for shorter duration at a higher fps.

The images obtained from the hi-speed camera are processed and analyzed in Davis 8.3.0 (from Lavision GmbH) using the cross-correlation technique. The correlation computation is done using Fast Fourier Transformation (FFT) with multi-pass iterations on interrogation windows with decreasing size - initial pass being on window size of 32 x 32 pixels and two more passes on 16 x 16 window size with 50% overlapping between the windows.

The instantaneous velocity vectors so obtained from the PIV measurements were checked for errors due to interpolation and smoothing techniques by calculating the divergence $\epsilon = |\partial u/\partial x + \partial v/\partial y|$. Assuming 2D flow in the free-stream region, ϵ can be equally split into u and v , and the error in each velocity component can be estimated as: $u_e = v_e = (\epsilon/2)\Delta x = (\epsilon/2)\Delta y$ where Δx and Δy are the pixel dimensions of the interrogation area used for velocity calculations in the x and y direction respectively. Please note that this cannot be done inside the cavity, because the cavity flow field is 3D whereas the velocity vectors are recorded by a 2D PIV system. For the instantaneous flow field in the free-stream region when the depth averaged mean velocity = 26 cm/s, the maximum divergence (ϵ) was found to be 15 sec^{-1} at a few points, although in majority of the flow field, the divergence was 5 sec^{-1} . However, in order to get the upper limit of the error, $\epsilon = 15 \text{ sec}^{-1}$ was used to calculate the errors: $u_e = v_e = (15/2) * 0.12 \text{ cm} = 0.9 \text{ cm/s}$. Thus, the maximum error = $(0.9/26)*100 = 3.4\%$ which is quite low and hence, acceptable.

3.3.2 Recording of particle trajectories in the XY plane using PIV

In all the PIV measurements conducted on the 5 planes discussed above, the flow field is recorded without introducing any particle in the planes. This is because the particle hardly stayed stationary in any of these planes. The 3-dimensionality of the cavity flow ensured that the particle has all the 3 possible movements - streamwise, spanwise and vertical in different regions of the cavity. In Phase 1, the plan-view (XZ) trajectories of the particle are recorded from the flume top under normal lighting conditions using a low-speed camera. This is done to have a general understanding of the particle movement under different experimental conditions.

In order to complement these plan-view trajectories, PIV measurements are also done to record the particle's vertical movement at the final stage of entrainment, i.e. from the cavity bed to the cavity top near the cavity downstream edge. The plane chosen for recording this XY movement is near the cavity sidewall close to $z = 0$. This position is chosen because at this location the particle has less spanwise movements than those along the cavity centerline where the particle is free to move towards either cavity corner. These XY particle trajectories and the flow field around it are recorded and analyzed by PIV and are discussed in detail in chapter 5.

3.4 Comparison of free-stream flow parameters for experiment set-ups in Phase 1 and Phase 2

To ensure that the flow field in both the set-ups of Phase 1 and 2 are the same, the velocity and turbulence profiles in the free-stream region in Phase 1 are compared with those in Phase 2 experiments. Figs. 3.4, 3.5 and 3.6 show vertical profiles of the streamwise velocity (V_x), the Reynolds shear stress (R_{xy}) and the turbulent kinetic energy (TKE), respectively measured 1 m upstream of the cavity leading edge using ADV/ADV in Phase 1 and PIV in Phase 2. The profiles are measured along the flume centerline, and show good agreement for both the experimental set-ups.

Figure 3.4 Comparison of V_x profiles in the free-stream region for Phase 1 (ADVP/ADV) and Phase 2 (PIV) experiments.

Due to limitations of the side-looking ADV, the vertical velocity, V_y could not be measured very close to the free surface; hence the R_{xy} and TKE profiles in Figs. 3.5 and 3.6 are cut short at 25 mm below the free-surface. The Reynolds shear stress shown in Fig. 3.5 is calculated using $R_{xy} = -\overline{V'_x V'_y}$, where V'_x and V'_y are the fluctuations in V_x and V_y respectively. Furthermore, the TKE profiles in Fig. 3.6 use only V'_x and V'_y such that $\text{TKE} = 0.5 (\overline{V'^2_x} + \overline{V'^2_y})$. This is because, PIV measurements are conducted along a plane, and the spanwise velocity, V_z cannot be recorded in such a case. From the good overlap obtained in both Phase 1 and Phase 2, it is concluded that flow field visualizations carried out in Phase 2 accurately replicate the flow conditions existing during the entrainment probability experiments in Phase 1.

Figure 3.5 Comparison of R_{xy} profiles in the free-stream region for Phase 1 (ADVP/ADV) and Phase 2 (PIV) experiments.

Figure 3.6 Comparison of TKE profiles in the free-stream region for Phase 1 (ADVP/ADV) and Phase 2 (PIV) experiments.

Chapter 4

Effect of cavity depth on particle entrainment

4.1 Introduction

Particle entrainment from inside a regular shaped rectangular cavity is significantly different from entrainment that occurs on flat sediment beds; the former being left unaddressed until now as seen in the literature review (Ch-2). With an increase in the cavity depth, D , the particle not only is required to overcome a higher vertical distance, but it also is subjected to changed flow conditions inside the cavity. An increase or decrease in D very likely changes the macro flow features inside the cavity in myriad possible ways, making entrainment from varying D a highly intricate phenomenon. In addition, the small scale randomness in any turbulent flow, exhibits its own complexities to this already complicated phenomenon. The difference between the steady flow outside the cavity and the unsteady flow inside is due to the sudden expansion in the channel configuration brought about by the introduction of a cavity in an otherwise straight open channel flume. This discontinuity in the flume leads to flow separation at the leading edge of the cavity, resulting in flow unsteadiness inside the cavity body. To have an improved understanding of these effects on particle entrainment, this chapter examines the role of cavity depth in affecting particle entrainment and explores the underlying entrainment mechanism. A brief conceptual model is provided first, followed by discussion of the experimental results.

4.2 Conceptual model

When a particle is placed at the cavity center, the motion that it may undergo is dependent on the flow characteristics inside the cavity. A flowchart is presented in Fig. 4.1, to show the multiple avenues available for the particle from its initial position at time = 0:

Figure 4.1 Flowchart depicting possible scenarios after a particle is released at the cavity center

The flowchart in Fig. 4.1 reveals that upon releasing a particle at the cavity center, it has two immediate options – either it moves away from the released position, or it remains at the same location. The movement can be further sub-divided into three more categories – upstream, downstream, or upward motion from the cavity center itself. These particle movements will become clearer in later Sections 4.3.3 and 5.4 where their trajectories are plotted. The movement of the particle towards the upstream edge of the cavity (scenario A) can most likely be attributed to the presence of a clockwise recirculation vortex pulling the particle backwards, as is illustrated in Fig. 4.2. If the horizontal force exerted by the vortex exceeds the frictional force acting on the particle, the particle enters this vortex zone, moves upstream in the cavity, and forgoes any possibility of entrainment. The presence of a recirculation bubble in a cavity has been reported in various studies as discussed in the literature review (Ch-2). Notable among such works are those of Haigermoser et al. (2008), Cicca et al. (2013), etc in deep cavities; Madi Arous et al. (2011), Zidanski et al. (2000), Reulet et al. (2002), and others in shallow cavities.

Figure 4.2 Flow topology showing a clockwise recirculation bubble covering majority of the cavity (Reproduced from Zidanski et al., 2000)

As soon as the particle is released at the cavity center, it may also be lifted immediately towards the free surface, and be entrained from the cavity straightaway (scenario B). This could be due to pressure fluctuations around the particle, unstable shear layer in the cavity, or suction (as mentioned in Sumer et al., 2001).

Another scenario for entrainment is when the particle moves towards the cavity downstream edge (scenario C). If the particle escapes from the cavity within a specified time, let's say t_o (scenario C1), it is considered an entrainment, and this entrainment can occur under different circumstances (as listed from C1.1 to C1.5) depending on the flow field near the cavity downstream edge. Some of these cases are discussed below.

Scenario C1.1 – When the particle is very close to the cavity downstream edge in the quiescent or stagnant region of the cavity flow field as depicted in Fig. 4.3, the particle may not experience much turbulence from the flow, and as a result, will show less or no movement. Assuming that an instantaneous force is applied to this particle resting on the cavity bed that results in its entrainment, the particle's trajectory and the minimum initial vertical velocity (u_{p0}) required to just overcome a distance equal to the cavity depth (D) can be modeled using Eqn. 4.1 or 4.2. This approach is based on the assumption that the particle trajectory is a straight vertical one, with the decelerating particle reaching the cavity top with a final velocity $u_{pf} = 0$ at $y = D$. Here, gravity (F_g) and drag force (F_D) are acting downwards and buoyancy (F_b) upwards. The equation of motion can be written as:

$$m(1 + C_m)a_{y,p} = -F_g - F_D + F_b \quad (4.1)$$

$$\text{or, } m(1 + C_m)\frac{d^2y}{dt^2} = -mg - \frac{1}{2}\rho C_D A_f \left(\frac{dy}{dt}\right)^2 + V_p \rho g \quad (4.2)$$

where m = particle mass, C_m = added mass coefficient, $a_{y,p}$ = particle acceleration, g = acceleration due to gravity, ρ = density of water, C_D = drag coefficient of the particle, A_f = particle area exposed to the flow, and V_p = particle volume.

The minimum initial vertical velocity u_{p0} needed to attain a height = cavity depth (D) can then be obtained by solving the above differential equation using the boundary conditions given below:

$$y = 0, t = 0; \frac{dy}{dt} = u_{p0}, t = 0$$

where $t = 0$ refers to the time when the said instantaneous force first acts on the particle.

Figure 4.3 Illustrative conceptual sketch of entrainment possibility when particle is in low turbulence region (scenario C1.1)

Scenario C1.2 – The possibility of entrainment also exists when the particle is close to the cavity downstream edge and it experiences an upward moving flow, instead of being in a quiescent flow as in previous scenario C1.1. This upward moving flow and the particle's location are shown in Figure 4.4. This is similar to scenario C1.1, with the exception that the relative velocity of the particle is now used in the drag force term. The equation of motion can be written as:

$$m(1 + C_m) \frac{d^2 y}{dt^2} = -mg - \frac{1}{2} \rho C_D A_f \left(v_{fy} - \frac{dy}{dt} \right)^2 + V_p \rho g \quad (4.3)$$

where v_{fy} = upward flow velocity at the cavity downstream edge.

This differential equation can also be solved with the same boundary conditions as used for Eqn. 4.2.

Figure 4.4 Illustrative conceptual sketch of entrainment possibility when particle is experiencing an upward moving flow (scenario C1.2)

Scenario C1.3 – In this case, particle located close to the cavity downstream edge experiences a horizontal flow (Figure 4.5), instead of an upward moving vertical flow as in previous scenario C1.2. Here, the particle experiences a drag force (F_D) in the horizontal direction and lift force (F_L) in the vertical direction. The motion of the particle is not in a straight vertical direction but is more like a projectile, adopting a curved trajectory from the bottom to the top of the cavity. Under this situation, two separate equations need to be solved, one in the x-direction and the other in the y-direction. The equations of motion can be written as:

$$m(1 + C_m) \frac{d^2x}{dt^2} = \frac{1}{2} \rho C_D A_f \left(v_{fx} - \frac{dx}{dt} \right)^2 \quad (4.4)$$

$$m(1 + C_m) \frac{d^2y}{dt^2} = -mg + \frac{1}{2} \rho C_L A_f \left(v_{fx} - \frac{dx}{dt} \right)^2 + V_p \rho g \quad (4.5)$$

where C_L = lift coefficient of the particle.

The above two differential equations can again be solved with boundary conditions similar to previous scenarios; using the initial particle position $(x, y) = (0, 0)$ at $t = 0$ and initial particle velocities $\left(\frac{dx}{dt}, \frac{dy}{dt}\right) = 0$ at $t = 0$.

Figure 4.5 Illustrative conceptual sketch of entrainment possibility when particle is experiencing a horizontal flow (scenario C1.3)

Scenario C1.4 – Particle entrainment can also be initiated near the cavity downstream edge when the flow is horizontal and the particle receives an impulse in the vertical Y-direction from the turbulent flow field in the cavity. In this case the impulse can be modeled as a square pulse and the upward particle motion be solved using the following equation, as proposed by Valyrakis et al. (2010):

$$m(1 + C_m) \frac{d^2 y}{dt^2} = -mg + F_L \{1 - H(t - T)\} + V_p \rho g \quad (4.6)$$

where F_L = lift force, and $H(t - T)$ is a unit step (Heaviside) function, defined by

$$H(t - T) = \begin{cases} 0, & t < T \\ 1, & t \geq T \end{cases}$$

Here, t is the time variable and T is the duration of the impulse. Thus in Eqn. 4.6, the lift force $F_L = 1$ for the duration of the impulse, i.e. for $t < T$, and $F_L = 0$ after the impulse has ceased to act, i.e. when $t \geq T$. However, unlike in Valyrakis et al. (2010), the particle in the present study is not shielded by any surrounding particles. Thus, the particle of interest will also experience a horizontal drag, which can be simply incorporated in the particle's horizontal motion using the same Eqn. 4.4.

Scenario C1.5 – In this case, the cause of entrainment is not just limited to the mean flow, fluctuating velocities, and impulses, but can also be the result of macro-turbulent flow structures in the cavity. An illustration of the temporal and spatial scale of the entire range of turbulent structures is shown in Fig. 4.6. Such macro-turbulent flow structures varying in size from the channel width (W) to the flow depth (H) have been observed on flat beds (Shvidchenko and Pender, 2001; Silva and Ahmari, 2009; Marquis and Roy, 2011) as well as in rectangular cavities (Ashcroft and Zhang, 2004). Since their size is dependent and restricted by the channel or cavity geometry, these too may influence entrainment from the cavity depending on the cavity depth (D). In this case, particle entrainment will be dependent on the size, strength and frequency of these large scale vortices, which in turn, are dependent on the cavity geometry or the cavity depth, D as is the case here.

Thus, it can be seen that entrainment from a cavity can be attained in multiple ways. This is because of the uncertainty and unsteadiness in turbulence that introduction of a geometric discontinuity such as a cavity can bring. The particle is expected to experience different flow fields in different regions of the cavity, most likely due to the size of the cavity itself; where its volume can be as much as 5000 times that of the particle volume and the cavity depth can range from 1.5 – 20 times the particle diameter. The randomness in the entrainment process is not just because of the fluctuating velocity as in flat beds, but also due to the spatially varying flow where the particle is not pinned to a fixed location but is free to move all over the cavity in a true 3-dimensional fashion under the competing influences of different flow regions and flow structures present inside the cavity.

Figure 4.6 Time scale and spatial scale of the entire range of turbulence shown as a function of the velocity frequency spectrum (Reproduced from Nikora, 2008).

In summary, entrainment from the cavity can occur immediately from its released position at the cavity center (scenario B) or from the cavity downstream region (scenarios C1.1 - C1.5). The force or energy required for the particle to be entrained, can be supplied by the flow's bulk motion, or the flow field turbulence, in the form of fluctuating drag, lift or impulse, be it from random fluctuations or from the large scale flow structures. When taking

into account a fluctuating velocity time series that is present in the cavity, the entrainment phenomenon takes a probabilistic aspect depending on the magnitude and frequency of the said fluctuations. Furthermore, considering entrainment by an impulse, where impulse $(I) = F\Delta t$, this stochastic aspect is heightened even more because now a large magnitude of F may not be enough; Δt needs to be sufficiently long for a high impulse and a successful entrainment to take place.

With entrainment from a cavity dependent on such a multitude of competing and interdependent factors, a frequentist approach to experimentally evaluate the entrainment probabilities is considered more appropriate here, instead of trying to estimate the complex relationship amongst these factors in a theoretical model. Accordingly, entrainment experiments are conducted under different cavity depths with different particles, and their results are presented and discussed in the following sections.

4.3 Experimental Results and Discussion

Based on the conceptual model presented in section 4.2, it is clear that particle entrainment from a cavity is dependent on a multitude of parameters as follows:

- Basic geometric configuration of the cavity such as the length (L), depth (D), particle release position, etc.;
- Free-stream bulk flow properties such as the mean flow velocity (u), bed shear velocity (u_*), flow depth (h) upstream of the cavity, flow depth (H) at the cavity, fluid properties such as density (ρ), dynamic viscosity (μ); and
- Particle characteristics such as the diameter (d) and density (ρ_s).

This section deals with the experimental results obtained at different cavity depths (D) for different particle types. This set of experiments will hence forth be referred to as Series 1. The test runs are primarily conducted under a single flow configuration (F1). However, 1

out of the 6 spherical particles used here, namely SP6, has been tested under 2 additional flow conditions (F2 and F3), for a better understanding of the dependence of entrainment probability (p) on cavity depth (D). Accordingly, the flow configurations, particle characteristics and entrainment probability data are provided in Tables 4.1, 4.2 and 4.3, respectively.

In Table 4.1, s_b , ν , Re_h , Fr_h , and Q refer to the flume bed slope, kinematic viscosity of water, Reynolds number based on the flow depth (h), Froude number based on the flow depth (h) and flow discharge, respectively.

Table 4.1 Free-stream flow configuration for Series 1 test runs

Flow Run	u (m/s)	u_* (m/s)	h (m)	s_b $\times 10^{-4}$	$\nu \times 10^{-6}$ (m ² /s)	Re_h	Fr_h	Q (m ³ /hr)
F1	0.260	0.0139	0.12	1.7	0.80	39000	0.240	55.0
F2	0.285	0.0155	0.12	2.0	0.80	42750	0.263	60.3
F3	0.322	0.0174	0.12	2.5	0.80	48300	0.297	68.2

In Table 4.2, m , d^* and τ^* refer to the particle mass, dimensionless particle size = $d(g(s-1)/\nu^2)^{1/3}$ and Shields parameter = $u_*^2/((s-1)gd)$. Here, g and s refer to acceleration due to gravity and specific gravity of the particle, respectively; and u_* is obtained by fitting the free-stream flow velocity profile to the logarithmic law of the wall. Moreover, particles SP1 - SP5 are not used in test runs F2 and F3, and their corresponding τ^* values have been left blank in Table 4.2. Similarly, the blank values in Table 4.3 are reflections that those particles have not been used for the corresponding cavity depth (D) in the tests. These test runs are not conducted because the entrainment probability (p) already attained its maximum value of 1.0 at a slightly higher D and continuing the experiments at lower D would give the same value of 1.0. All the entrainment probability values listed in Table 4.3 are conducted for 50 trials, except for those marked with an asterisk for which 200

trials are used. In all these experiments, the free-stream flow depth (h) and the cavity length (L) are kept constant at 0.12 m and 1.0 m, respectively. The particle release position is similarly unvaried at the center of the rectangular cavity.

Table 4.2 Summary of relevant particle properties used in Series 1 test runs

Particle Type	$d \times 10^{-2}$ (m)	$\rho \times 10^3$ (kg/m ³)	$m \times 10^{-3}$ (kg)	d^*	τ^* (@F1)	τ^* (@F2)	τ^* (@F3)
SP1	2.35	1.01	6.86	125.77	0.0838	-	-
SP2	1.38	1.03	1.42	106.52	0.0476	-	-
SP3	0.62	1.10	0.14	71.49	0.0318	-	-
SP4	0.60	1.11	0.13	71.41	0.0298	-	-
SP5	0.78	1.10	0.27	89.93	0.0253	-	-
SP6	0.63	1.20	0.16	91.52	0.0156	0.0194	0.0245

Table 4.3 Entrainment probabilities under different experimental parameters (Series 1 test runs)

D (mm)	H (mm)	Entrainment Probability (p)							
		@ F1						@ F2	@ F3
		SP1	SP2	SP3	SP4	SP5	SP6	SP6	SP6
10	130	-	-	-	-	-	1	1	1
17	137	-	-	-	-	1	0.88	0.98	1
25	145	-	-	-	-	1	0.18*	0.66	0.98
29	149	-	-	-	-	1	0.20*	0.62	0.94
41	161	1	1	1	1	0.94	0.30*	0.50	0.90
53	173	1	1	1	1	0.92	0.48	0.60	0.74
65	185	1	1	1	1	0.94	0.32	0.44	0.52
77	197	0.98	0.94	0.92	0.90	0.82	0.16	0.14	0.22
81	201	0.82	0.62	0.66	0.54	0.40	0.08	0.10	0.10

85	205	0.58	0.44	0.42	0.34	0.24	0.04	0.04	0.06
89	209	0.38	0.24	0.26	0.26	0.12	0.02	0.02	0.04
101	221	0.12	0.04	0.06	0.06	0.06	0	0	0
113	233	0.04	0	0	0	0	0	0	0

4.3.1 Particle Entrainment Probabilities

The entrainment probability curves for all the 6 particles under different test conditions are plotted in Fig. 4.7. The figure shows the entrainment probabilities (p) as a function of D/H . Each reversed S-curve represents a different Shields parameter: curves CR6 - CR8 represent a single particle SP6 but subjected to 3 different flow configurations F1 - F3, respectively, and the remaining curves CR1 - CR5 for particles SP1 - SP5 respectively under the same flow condition F1.

Figure 4.7 Entrainment probability (p) as a function of D/H

Figure 4.7 clearly shows that particle entrainment from a rectangular cavity is indeed stochastic, with entrainment probability (p) varying from 0 to 1 for different values of D/H . Choosing a single curve from Fig. 4.7, say CR1 as an illustration, for which τ^* is constant; it can be seen that particle entrainment is occurring over a wide range of cavity depth, D with varying success rate, p . The data also reveals the non-existence of a unique critical value of D/H that definitively demarcates zero entrainment from 100% entrainment; as is otherwise observed in the Shields diagram for sediment entrainment on a flat bed or in Sumer et al.'s (2001) diagram for particle entrainment from an armor block cavity. Thus, adopting a probabilistic approach rather than a threshold or deterministic approach seems to be more appropriate to describe particle entrainment from a cavity.

However, it must be stated that although a perfect reverse S-trend is observed in the curves CR1 - CR4, the remaining curves with lower τ^* (for the 2 particles - SP5 and SP6) exhibit variations at different values of D/H . This deviation is most obvious for the curve CR6 with the lowest τ^* value (i.e. 0.0156), where the curve comprises two turning points, with the local minima and maxima occurring at $D/H = 0.17$ and 0.3 respectively. A closer examination reveals that the 3 data points causing this anomaly occur at $D = 25$ mm, 29 mm and 41 mm. In order to verify the deviation, test at the 3 cavity depths ($D = 25$, 29 and 41 mm) are each repeated 4 times, thus computing the entrainment probability using 200 trials, a quadruple increase from the otherwise standard 50 trials. Notwithstanding this increase in trials, the CR6 curve still continues to exhibit the same behavior.

To investigate this variation, more test runs with the SP6 particle are conducted with 2 additional flow conditions F2 and F3 that have higher free-stream velocity than F1. These are the curves CR7 (dashed line) and CR8 (dash-dot line). These new entrainment probability curves reveal that the anomaly exhibited in CR6 reduces gradually when u (or rather τ^*) is increased; with the curve CR8 at F3 displaying an exact shape as that of the curve CR5 at F1, or similar to the curves CR1 - CR4 at F1. The deviation is not just affecting the SP6 particle, but SP5 particle as well, as seen in the top portion of the CR5 curve for $D = 41$ and 53 mm. Since this variation is observed only in the curves CR5 - CR8

for a small range of D/H , it is surmised that it is a reflection of the interplay of SP6's and SP5's low τ^* under low values of D , for this particular range of D/H . In fact, SP6 and SP5 have the lowest τ^* amongst all the 6 particles, making them more difficult to be entrained when compared to the other particles under the same flow and cavity configurations. However, it would have been generally thought that in any curve C1 - C8, a lower D would result in a higher p , as the particle has a shallower cavity depth to jump over for entrainment. This, being not the observation here at several D values, indicates that some other factors must be present to cause this anomaly.

The deviation in the CR6 curve can be accounted for if isotropic random velocity fluctuations and anisotropic macro-turbulence present in the cavity are both taken into account in an integrated manner. Published research studies have shown that turbulent eddies in a flow, range from the micro-scale (in millimeters) to the macro-scale (limited only by the channel geometry) with the maximum vertical size of the large scale eddies being close to the flow depth (Yokosi, 1967; Nezu and Nakagawa, 1993; Shvidchenko and Pender, 2001; Marquis and Roy, 2013; Nikora, 2008). Fig. 4.6 depicts the spatial scale of the entire range of turbulence. It is this combination of micro-turbulence and macro-turbulence in the cavity that is likely responsible for not only the entrainment but also the stochastic features observed in this study. This is akin to the entrainment scenario C1.5 discussed earlier in section 4.2 under the conceptual model, where the drag force, F_D and lift force, F_L may be due to the large scale eddies in the cavity flow regime.

When $D = 25 \text{ mm} - 41 \text{ mm}$, the vertical extent of the macro-turbulent flow structures in the cavity is evidently limited by the total flow depth in the cavity, H . As per the standard energy cascade, these comparatively smaller flow structures will have lower turbulent energy content (Nezu and Nakagawa, 1993; Pope, 2000) when compared to the flow structures where H is higher ($D > 41 \text{ mm}$). This reduced eddy size and lower energy content can decrease the entrainment probability, p , resulting in the significant sagging portion of the curves CR6 and CR7, and to a limited extent, in the curves CR8 and CR5. Additionally, when $D < 25 \text{ mm}$, the cavity depth to the total flow depth ratio, $D/H < 0.17$. Under such a

condition, the presence or absence of a cavity is hardly significant, because the incoming bulk flow properties are more dominant in causing entrainment than any eddies present in this comparatively shallower cavity. As a result, the particles are readily entrained at these very shallow cavity depths. This leads the portion of the curves CR6 and CR7 to again fall into the generalized standard shape of the entrainment probability curves at very low D . The entrainment process in this case is similar to that on flat beds, or scenario C1.3 and C1.4 discussed in section 4.1 (conceptual model) where the particle experiences drag and lift from a horizontal streamwise flow.

In summary, the cavity depth dependent flow structures, bulk flow property's dominance at very shallow D , coupled with SP6's lowest τ^* value cause the formation of the particular shape of the CR6 and CR7 probability curves. However, when the approach shear velocity u_* or τ^* is increased, the probability function reverts to the expected trend, as is seen in the curve CR8. This is because higher turbulent intensities now negate both the lower τ^* of the SP6 particle and the lower turbulent energy content of the cavity eddies for $25 \text{ mm} \leq D \leq 41 \text{ mm}$. Thus, a combination of low τ^* and cavity depth dependent flow structures bring about a reduction in p in the CR5 - CR8 curves, which is otherwise absent for particles SP1 - SP4. This interplay of cavity, particle and bulk flow properties in effecting entrainments is further examined in Section 4.3.3 where the particle entrainment mechanisms and trajectories are discussed.

The entrainment probabilities in Fig. 4.7 need to be interpreted in conjunction with error margins at reasonable confidence levels. To this end, the 95% confidence intervals (C.I.) are calculated for this entrainment phenomenon based on the binomial distribution model. These error margins vary with the proportion of successes to the maximum number of trials, and are lower when $p = 0$ and 1, and higher when number of successes and failures are nearly equal. Theoretically calculating the 95% C.I. using the Wilson-score method (Eqn. 4.7) gives a minimum error margin of ± 0.0714 (at $p = 0, 1$) and a maximum of ± 0.1382 (at $p = 0.4, 0.6$).

$$C.I. = \frac{1}{1 + \frac{1}{n}Z_n^2} \left[p + \frac{1}{2n}Z_n^2 \pm Z_n \sqrt{\frac{1}{n}p(1-p) + \frac{1}{4n^2}Z_n^2} \right] \quad (4.7)$$

where p , n , and Z_n are the entrainment probability, total number of trials, and the $(1 - \varepsilon/2)$ percentile of a standard normal distribution with ε = error percentile = 0.05, respectively.

Notwithstanding the above theoretically computed error margins of ± 0.0714 to ± 0.1382 , the probabilistic trend depicted in Fig. 4.7 still holds. Moreover, it has already been shown in Ch-2 that the error margins calculated experimentally are as low as ± 0.04 rather than the higher theoretical error value of ± 0.1382 , when n is doubled from 50 to 100. Hence, it can be safely concluded that the entrainment probabilities in Fig. 4.7 are reasonably accurate and are likely to have lower error margins than those computed theoretically using Eqn. 4.7.

4.3.2 Particle Entrainment Time Distributions

If entrainment from a cavity is deterministic or based on a threshold criterion, the time taken for a particle to be entrained (t_e), say for SP3 at $D = 53$ mm, will be a constant value for all the 50 trials. However, if it is not, then recording the particle entrainment durations can help to ascertain if the probabilistic hypothesis assumed here is justified or not. To this end, entrainment durations are recorded for all the particles at all the cavity depths, and the results are presented in this section.

The entrainment probabilities shown previously in Fig. 4.7 are based on observation duration (t_o) of 2 minutes. However, in several test runs, the particle is allowed to be subjected to the turbulent cavity flow field for longer durations, in excess of 2 minutes, in order to have a better understanding of the entrainment process. The time at which a particle is entrained is recorded (data is presented in Appendix 1), and their probability density functions (PDFs) are plotted in Fig. 4.8. However, to avoid clutter, the PDFs are plotted only for a few test runs (particles SP1 - SP6 at $D = 53, 65, 81$ mm under flow condition F1). Nevertheless, all the other entrainment time distributions that are not plotted also follow the same trend exhibited in the figure.

**Figure 4.8 PDFs of entrainment time (t_e) for particles SP1 - SP6 at $D = 53, 65, 81$ mm
(please note the different axes used in the subplots)**

In Fig. 4.8, empirical PDF values of entrainment durations are shown as circles, and are fitted to a log-normal distribution represented by the solid lines. The variability in the data and the long tail in all the PDFs indicate that entrainment is occurring at variable durations, t_e instead of at a constant time interval as it would have, had the process been purely deterministic. The log-normal distribution generally fits majority of the empirical PDF values, irrespective of whether all 50 entrainments take place within a 2 minute duration or not. Moreover, all the PDFs are single-peak functions, with the peaks occurring at a value well below the stipulated observation duration of $t_o = 2$ minutes. This holds true even for the SP6 PDFs at $D = 53$ mm and 65 mm where t_o extends to as long as 10 minutes, with the peaks occurring at $t_e = 30$ sec and 90 sec, respectively. The occurrence of PDF peaks at $t_e \leq 2$ mins in all the curves further corroborates limiting the maximum observation duration to 2 minutes, and validates the entrainment probability curves plotted in Fig. 4.7, at least for all the tests conducted in this study.

Most importantly, these PDFs portray the randomness and variability at which a particle is entrained from the cavity, even when all test parameters are kept constant. This is evident in all the PDFs, and especially in the SP6 PDFs at $D = 53$ mm and 65 mm where t_e ranges from as short as 10 seconds to as long as 10 minutes, and beyond. This drastic variation in the entrainment durations under the same test condition can only be attributed to the randomness in the velocity fluctuations and the presence of random macro-turbulent eddies in the cavity flow field. On the one hand, this behavior sometimes leads to an immediate and spontaneous particle entrainment in a few seconds, and at other times, entrainment occurs after as long as 10 minutes. These random time durations for particle entrainment further reinforce the probabilistic hypothesis considered here.

Fig. 4.8 also shows that the PDFs are right-skewed with longer tails as D increases. In addition, in shallower D , the entrainment durations are narrowly distributed with PDFs having steep gradients, indicating a shift of dominance from the random cavity flow structures to the less random bulk flow variables as the major cause behind the entrainments. Thus, any of the entrainment scenarios listed in section 4.1 from C1.1 to C1.5 can be applicable here - be it due to the bulk flow, velocity fluctuations, large scale eddies,

impulse, or a combination of these. With the PDFs in Fig. 4.8 complementing the entrainment probability curves in Fig. 4.7, the inherent stochastic nature that governs particle entrainment from a rectangular cavity gets fully highlighted here.

4.3.3 Particle Trajectories and Entrainment Mechanism

In this section, the entrainment mechanism is discussed in greater details using the plan-view particle trajectories in Fig. 4.9 and a 3-dimensional illustrative sketch in Fig. 4.10. Three animations (3-dimensional) of the entrainment process are also included, accessible via web link¹, to help readers visualize the complete entrainment process as observed during the experiments. In Fig. 4.9, the particle trajectories are plotted over the entire cavity dimensions, with the horizontal axis representing the cavity length, $L = 1.0$ m, and the vertical axis representing the cavity width, $W = 0.49$ m. The trajectories show the particle's motion inside the cavity starting from its release position at the cavity center ($X = 0.5$ m, $Z = 0.245$ m) until it is either entrained from the cavity along the downstream edge or is trapped in the cavity upstream region with little scope for escape. X and Z refers to the streamwise direction and the spanwise direction as defined in the coordinate system in Ch-3. The trajectories shown here are representative of all the particles from SP1 to SP6.

The particle trajectories are categorized into the following stages based exclusively on the cavity depth, D , with D incrementally increasing between the stages:

- Stage 01: particle movement is only in the downstream direction with essentially straight pathlines. Here, $p = 1.0$ and entrainment duration, $t_e \leq 2$ mins;
- Stage 02: particle motion is in the downstream direction accompanied with spanwise movements; with $0 < p \leq 1.0$ and $t_e \in \mathbb{N}$, where $\mathbb{N}$ = set of positive integers;
- Stage 03: particle moves either upstream with no possibility of entrainment i.e., $p = 0$ and $t_e = \infty$ or in the downstream direction with $0 < p < 1.0$, and $t_e \in \mathbb{N}$; and
- Stage 04: particle movement is only in the upstream direction resulting in zero entrainment, i.e. $p = 0$ and $t_e = \infty$.

¹ <https://www.dropbox.com/sh/9nwdy17s4e9luzr/AACZITDnpdTBArfOE9tCng9a?dl=0>
shortened url: <https://tinyurl.com/gvcgezww>

Figure 4.9 Two-dimensional plan view particle trajectories (a) Stage 01; (b) Stage 02; (c) Stage 03; (d) Stage 04 (all units in meters)

It is to be noted that Stage 01 and Stage 02 both correspond to the entrainment scenario C (discussed in section 4.2) where particles move downstream from their release position, followed by their entrainment. Stage 03 includes both scenario A (particle upstream movement) and scenario C (particle downstream movement). Stage 04 comprises exclusively scenario A, i.e. all particles move upstream in the cavity and entrainment probability $p = 0$. Scenario B, where entrainment takes place immediately from its release position, is not witnessed in any of these stages. To reiterate,

- Stage 01, Stage 02: scenario C (particle moves downstream);
- Stage 03: includes both scenario A (particle move upstream) and scenario C (particle moves downstream);
- Stage 04: scenario A (particle move upstream) and zero entrainment;
- No scenario B is witnessed.

The different stages are discussed in more details as follows:

Stage 01: This stage is shown in Fig 4.9(a) and can be further divided into two sub-categories:

- Stage 01A (green dashed lines) where D is minimum, and the flow inside the cavity is predominantly 2-dimensional, similar to that on a flat bed. This is also evident in the particle's straight pathlines without any spanwise deviations. The particles take the shortest path to entrainment, and are essentially driven by the bulk momentum of the approach flow, rather than random eddies in the cavity. As a result, the entrainment probability, p in this stage is 1.0 and entrainment durations, t_e well below 2 minutes.
- Stage 01B (blue solid lines) where a slight transition in the cavity flow field is seen with an increase in D . The flow transitions from a strictly 2-dimensional flow to a weak 3-dimensional flow. Although the particles reach the cavity downstream edge in straight paths as in Stage 01A, they exhibit a tendency to move spanwise along the cavity edge.

Stage 02: The cavity flow field in this stage reaches a complete transition to a 3-dimensional one, with transverse particle movements sometimes beginning at the location very close to the cavity center (see Fig. 4.9(b)), instead of near the downstream cavity edge as seen previously in Stage 01B. This 3-dimensional cavity flow with its secondary currents directs more and more particles spanwise and towards the cavity corners. The entrainments are likely influenced by the random eddies in the cavity, resulting in widely varying values of p and t_e in this stage. In addition, the particles are observed to entrain more from the cavity corners than from the center.

Stage 03: In this stage, some particles are seen to travel downstream (Stage 03A) while others upstream (Stage 03B) inside the cavity (Fig. 4.9(c)). The upstream movement of the particle is due to the formation of a clockwise rotating recirculation vortex that extends from the upstream cavity edge to the cavity center. However, due to the eddy's comparatively low strength and the intermittent changes in its size and extent, it does not have 100% success in drawing all the particles upstream and consequently some particles still make it to the downstream cavity edge. It must be noted that particles in the cavity upstream region exhibit slower movements compared to the ones in the downstream region, and are doomed to be confined in the cavity once they reach upstream, with no possibility of entrainment whatsoever. The reason that more variations in particle trajectories are observed in the cavity downstream region when compared to the upstream zone is likely due to higher turbulence in the downstream area as reported in laminar as well as turbulent studies on rectangular cavities such as Cicca et al. (2013) and Haigermoser et al. (2008), respectively. The upstream movement of particles coupled with an increase in D , leads to a simultaneous decrease in the entrainment probability, p along with longer entrainment durations, t_e in Stage 03.

Stage 04: This final stage is reached when the cavity depth is the maximum, and the upstream movement of particles has intensified to such an extent that no particles are able to reach the downstream cavity edge anymore. The upstream recirculation eddy of Stage 03 has grown larger and stronger in Stage 04, with no particles being able to escape it; thus bringing all entrainments to a complete halt. As a result, the entrainment probability, $p = 0$

for all the particles in this stage. This existence of an upstream recirculation bubble spread across the majority of the cavity length for similar cavity configuration has also been reported by Reulet et al. (2002).

Readers are encouraged to refer to the 3 animations, (accessible via the web link mentioned in the beginning of this section) corresponding to stages - 01A, 02 and 04. Since Stage 03 is an intermediate stage between 02 and 04, and has similar trajectories as in Stage 02 (downstream movement) and Stage 04 (upstream movement), no separate animation file is presented for Stage 03 alone.

In the flowchart in Fig. 4.1, particle movement upon its release is categorized into 3 major divisions - particle movement upstream (scenario A) and downstream (scenario C) in the cavity, and immediate entrainment upon release (scenario B). However, the particle trajectories in Fig. 4.9 show that even movement inside the cavity can be further sub-divided into many stages depending on the cavity depth D , which again may significantly influence the entrainment values and the entrainment mechanism as discussed in scenarios C1.1 - C1.5. A 3-dimensional illustrative sketch of the entrainment process is provided in Fig. 4.10 where the top sketch depicts the entrainment process due to the random small-scale and large-scale eddies near the downstream cavity edge, and the bottom sketch shows the entrapment of a particle by the upstream recirculation eddy. While the former can probably lead to a successful entrainment, the latter ends in an entrainment failure.

The transition from a 2-dimensional flow field in the cavity to a 3-dimensional one as seen in Stages 01 and 02 is due to the expansion of the flume geometry with an increase in D . This results in flow separation near the cavity edges and formation of secondary currents and random eddies in the cavity. These random eddies and velocity fluctuations in the turbulent flow field, in turn, provide the required lift, F_L and drag force, F_D that result in the stochastic nature of particle entrainment. The randomness in the flow field leads to entrainment, sometimes in a few seconds or minutes, and at other times resulting in no entrainment at all. Hence, it is patently clear that particle entrainment is a function of both the large-scale eddies with higher turbulent energy and the small-scale random eddies and

velocity fluctuations; and a particle when exposed to a favorable combination of such events for sufficiently long duration, leads to its sporadic entrainment from the cavity.

Figure 4.10 Three-dimensional illustrative sketch of the entrainment mechanism: (Top) entrainment due to downstream fluctuations and random eddies; (Below) no-entrainment because of upstream recirculation eddy

4.4 Concluding Remarks

Particle entrainment from a rectangular cavity is discussed in the chapter with the cavity depth, D being the primary parameter under focus. A conceptual flowchart is presented, outlining the various possible scenarios that can result in a successful entrainment or a failure. Equations of motion under these scenarios are provided which can relate the flow condition with the particle motion at the time of entrainment. The multitude of conditions that can theoretically result in an entrainment seem to show that entrainment from a cavity is highly stochastic, especially when considering the random velocity fluctuations and eddies.

Subsequently, laboratory experiments are carried out to investigate this entrainment behavior, and the results validate the probabilistic hypothesis proposed in this study. The results show that particle entrainment from a cavity is primarily a stochastic phenomenon, hitherto unaddressed in similar studies, e.g., Sumer et al. (2001), Dwivedi et al. (2010) and Lai et al. (2010). Entrainments are found to occur randomly at widely varying time intervals, mostly due to the particle experiencing all the randomness that exists in the turbulent flow field of the cavity.

Entrainment probability distributions with respect to D/H show that entrainments occur for a wide range of particle properties and cavity depths, with varying degree of success (p). No critical or threshold value of D/H is observed which can strictly demarcate $p = 0$ and 100% entrainment probability. This is in contrast to the customary Shields' diagram as well as Sumer et al.'s (2001) diagram developed with tests on sediment entrainment from armor block cavities. Hence, the study confirms that adopting a threshold value approach for this entrainment behavior is not an appropriate one.

The entrainment timescales further validate the probability hypothesis, with entrainments being recorded at random time durations from a few seconds to a few minutes, and their PDFs showing a generally acceptable fit to the log-normal distribution. Thus, the stochastic nature of these entrainments is exhibited in both the entrainment probability distributions of Fig. 4.7 as well as the entrainment time PDFs of Fig. 4.8. It must be stated that this stochastic nature is present even when the bulk flow properties, such as flow discharge (Q), mean flow velocity (u), bed shear velocity (u_*) and flow depth (h) are kept constant. The only variables are the cavity depth, D , particle diameter, d and particle density, ρ_s .

When studying particle entrainment from a cavity, one could deduce that the relationship between entrainment probability (p) and cavity depth (D) is fairly straightforward: when D decreases, p should increase. However, a closer examination of the probability curves in Fig. 4.7 (CR5 - CR8) and Figs. 4.9 - 4.10 on the trajectories and entrainment mechanism shed a different light. The curves C6 and C7 in Fig. 4.8 highlight that entrainment from a cavity is a highly complex phenomenon - with its success dependent on the interplay

between the random velocity fluctuations, cavity depth-dependent large scale flow structures, particle properties as well as the bulk flow property, such as mean flow velocity. The complexities of the entrainment behavior are further elaborated in the particle trajectory plots, which show that with increasing D , the flow, which was initially 2-dimensional in nature transitions into a 3-dimensional one with secondary flow, random small-scale and large-scale eddies. Moreover, a dominant flow reversal in the cavity causes particles to move upstream rather than downstream. Hence, investigating this intricate entrainment mechanism brings to light the underlying complexities and interdependencies of different parameters affecting particle entrainment from a rectangular cavity; and the shifting dominance of a set of variables over another, sometimes lead to quick entrainment within a few seconds and sometimes no entrainment is witnessed even for longer observation durations. This in turn leads to widely varying entrainment successes, entrainment durations and particle trajectories, as seen in this chapter. In view of these complex flow behavior and entrainment process, this phenomenon's dependence on other variables are studied more extensively and PIV tests are conducted, whose results are presented in the following chapters.

Chapter 5

Particle entrainment: free-stream velocity effects and cavity flow field characteristics

5.1 Introduction

In the preceding chapter, the role of cavity depth (D) on particle entrainment was examined. Continuing with the investigation, this chapter explores how the free-stream velocity (u) affects the particle entrainment probability (p) from a rectangular cavity. The cavity flow field obtained from Particle Image velocimetry (PIV) measurements are also discussed to provide a better understanding of particle entrainment from the cavity.

5.2 Entrainment probability: experimental conditions and results

Experiments are conducted using different particle types under a wide range of free-stream velocities, with all other parameters kept constant, including the cavity geometry. The cavity length (L) and cavity depth (D) are fixed at 100 cm and 5.3 cm, respectively. Here, the free-stream velocity (u) refers to the time-averaged and depth-averaged streamwise velocity prevailing at 1 m upstream of the cavity leading edge. The different flow configurations used are listed in Table 5.1. The particle types used in these test runs are SP2, SP4, SP5 and SP6, whose properties were already listed in Table 4.2. However, for the sake of easy reference, the properties of these 4 particles are reproduced in this chapter in Table 5.2.

During the experiments, particle SP1 (see Table 4.2) with its neutrally buoyant characteristics ($\rho_s = 1.01 \text{ g/cc}$) proved difficult to be placed in a stable position inside the cavity especially at high flow discharge, and hence is dropped from the test runs. Furthermore, particle SP3 is not used in this test series because it shares similar properties with SP4 in both particle diameter as well as particle density and hence using only one out

of these two is considered adequate: $d = 0.62 \text{ cm}$, $\rho_s = 1.1 \text{ g/cc}$ for SP3 and $d = 0.6 \text{ cm}$, $\rho_s = 1.11 \text{ g/cc}$ for SP4. Moreover, using 4 particle types is considered sufficient to capture the role of particle properties in the entrainment process.

Table 5.1 Free-stream flow configuration for Series 2 experiment runs (for cavity configuration: $L = 100 \text{ cm}$; $D = 5.3 \text{ cm}$)

Serial. no.	u (m/s)	u_* (m/s)	H (m)	s_b $\times 10^{-4}$	$\nu \times 10^{-6}$ (m^2/s)	Re_h	Fr_h	Q (m^3/hr)
1	0.078	0.0043	0.173	0.2	0.8	11700	0.072	16.5
2	0.123	0.0067	0.173	0.4	0.8	18450	0.113	26.0
3	0.151	0.0082	0.173	0.6	0.8	22650	0.139	32.0
4	0.187	0.0101	0.173	0.9	0.8	28050	0.172	39.6
5	0.211	0.0116	0.173	1.1	0.8	31650	0.194	44.7
6	0.260	0.0139	0.173	1.7	0.8	39000	0.240	55.0
7	0.285	0.0155	0.173	2.0	0.8	42750	0.263	60.3
8	0.322	0.0174	0.173	2.5	0.8	48300	0.297	68.2
9	0.342	0.0186	0.173	2.9	0.8	51300	0.315	72.4
10	0.385	0.0210	0.173	3.7	0.8	57750	0.355	81.5

Table 5.2 Particles used in Series 2 experiment runs

Particle	$d \times 10^{-2}$ (m)	$\rho \times 10^3$ (kg/m^3)	$m \times 10^{-3}$ (kg)	d^*
SP2	1.38	1.03	1.42	106.52
SP4	0.60	1.11	0.13	71.41
SP5	0.78	1.10	0.27	89.93
SP6	0.63	1.20	0.16	91.52

Table 5.3 lists the entrainment probabilities for all the 4 particles calculated using 50 trials under different flow configurations. The critical Shields parameter τ_{cr}^* is calculated using the formula developed by Whitehouse et al. (2000) where:

$$\tau_{cr}^* = \frac{0.24}{d_*} + 0.055[1 - \exp(-0.02d_*)] \quad (5.1)$$

The critical Shields parameter $\tau_{cr-sumer}^*$ in Table 5.3 represents entrainment of a particle from gaps between stones of size D_s analogous to cavity depth (D) here and is calculated using the formula proposed in Sumer et al. (2001) where:

$$\tau_{cr-sumer}^* = 0.3 + 3 \left(\frac{d}{D_s} \right)^{-0.15} \exp \left(-7.5 \frac{d}{D_s} \right) \quad (5.2)$$

From Table 5.3, it can be noted that the entrainment probability (p) does not simply have the binary values 0 and 1 but is spread over between 0 - 1 across a wide range of τ^* among all the 4 particles. There is no critical or threshold value of τ^* immediately below which $p = 0$ and above which $p = 1$. This probabilistic trend in particle entrainment from a cavity is in direct contrast to the Shields' diagram and Sumer et al.'s (2001) study where a critical τ^* value is recommended for defining entrainment from sediment beds and armor block cavities, respectively. However, it is to be noted that the Shields parameter (τ^*) in Table 5.3 makes use of the shear velocity (u_*) prevailing at 1 m upstream of the cavity leading edge, rather than the local u_* . Calculating u_* from the free-stream upstream location gives a better representation of the global flow field regime and is more accurate because of the steady uniform flow prevailing there, thus resulting in a proper log-law fit to the velocity profile from which u_* is obtained. This is in contrast to the highly turbulent, unsteady and non-uniform flow present locally inside the cavity and especially near the cavity downstream edge where particle entrainment actually takes place, and the velocity profile is anything but a log-law fit (refer to Figs. 5.3 - 5.8, especially Fig. 5.4). This comparison of flow fields outside and inside the cavity will be easier to visualize in the succeeding section 5.3 where detailed PIV results of the flow field are presented.

Table 5.3 Entrainment probabilities under different free-stream velocities for constant cavity configuration

Particle Type	u (m/s)	p	τ^*	τ_{cr}^*	$\frac{\tau^*}{\tau_{cr}^*}$	$\tau_{cr-sumer}^*$	$\frac{\tau^*}{\tau_{cr-sumer}^*}$	R
SP2	0.078	0	0.0046	0.0507	0.0898	0.8208	0.0055	66.05
	0.123	0.42	0.0111	0.0507	0.2179	0.8208	0.0135	42.39
	0.151	0.68	0.0166	0.0507	0.3264	0.8208	0.0202	34.63
	0.187	0.86	0.0251	0.0507	0.4952	0.8208	0.0306	28.12
	0.211	0.98	0.0331	0.0507	0.6532	0.8208	0.0404	24.48
	0.260	1	0.0476	0.0507	0.9380	0.8208	0.0580	20.43
	0.285	1	0.0592	0.0507	1.1663	0.8208	0.0721	18.32
	0.322	1	0.0745	0.0507	1.4698	0.8208	0.0908	16.32
	0.342	1	0.0852	0.0507	1.6795	0.8208	0.1038	15.27
	0.385	1	0.1086	0.0507	2.1409	0.8208	0.1323	13.52
SP4	0.078	0	0.0029	0.0452	0.0632	2.0795	0.0014	80.23
	0.123	0.24	0.0069	0.0452	0.1535	2.0795	0.0033	51.49
	0.151	0.6	0.0104	0.0452	0.2299	2.0795	0.0050	42.07
	0.187	0.9	0.0158	0.0452	0.3488	2.0795	0.0076	34.16
	0.211	0.98	0.0208	0.0452	0.4600	2.0795	0.0100	29.74
	0.260	1	0.0298	0.0452	0.6606	2.0795	0.0144	24.82
	0.285	1	0.0371	0.0452	0.8214	2.0795	0.0178	22.26
	0.322	1	0.0468	0.0452	1.0351	2.0795	0.0225	19.83
	0.342	1	0.0534	0.0452	1.1828	2.0795	0.0257	18.55
	0.385	1	0.0681	0.0452	1.5077	2.0795	0.0328	16.43

(Contd.)

(Contd.)

Particle Type	u (m/s)	p	τ^*	τ_{cr}^*	$\frac{\tau^*}{\tau_{cr}^*}$	$\tau_{cr-sumer}^*$	$\frac{\tau^*}{\tau_{cr-sumer}^*}$	R
SP5	0.078	0	0.0024	0.0486	0.0498	1.6261	0.0015	89.59
	0.123	0	0.0059	0.0486	0.1208	1.6261	0.0036	57.50
	0.151	0.12	0.0088	0.0486	0.1809	1.6261	0.0054	46.98
	0.187	0.36	0.0133	0.0486	0.2745	1.6261	0.0082	38.14
	0.211	0.58	0.0176	0.0486	0.3621	1.6261	0.0108	33.21
	0.260	0.92	0.0253	0.0486	0.5199	1.6261	0.0155	27.72
	0.285	0.94	0.0314	0.0486	0.6465	1.6261	0.0193	24.85
	0.322	1	0.0396	0.0486	0.8147	1.6261	0.0243	22.14
	0.342	1	0.0452	0.0486	0.9310	1.6261	0.0278	20.71
	0.385	1	0.0576	0.0486	1.1867	1.6261	0.0354	18.35
SP6	0.078	0	0.0015	0.0488	0.0307	1.9931	0.0008	114.01
	0.123	0	0.0036	0.0488	0.0744	1.9931	0.0018	73.17
	0.151	0	0.0054	0.0488	0.1115	1.9931	0.0027	59.79
	0.187	0.04	0.0083	0.0488	0.1691	1.9931	0.0041	48.54
	0.211	0.2	0.0109	0.0488	0.2231	1.9931	0.0055	42.26
	0.260	0.48	0.0156	0.0488	0.3203	1.9931	0.0078	35.27
	0.285	0.6	0.0194	0.0488	0.3983	1.9931	0.0098	31.63
	0.322	0.74	0.0245	0.0488	0.5019	1.9931	0.0123	28.18
	0.342	0.86	0.0280	0.0488	0.5735	1.9931	0.0140	26.36
	0.385	1	0.0357	0.0488	0.7311	1.9931	0.0179	23.35

5.2.1 Comparison of entrainment probability with other studies

In this section, the present study's Shields' parameter (τ^*) values are compared with the critical values found in the Shields' diagram. These critical values can be found in Table 5.3 under the column τ_{cr}^* . In Fig 5.1, the entrainment probability (p) is plotted as a function of

two different ratios – one is τ^*/τ_{cr}^* and another one is $\tau^*/\tau_{cr-sumer}^*$ (discussed in the next paragraph). The data in Fig. 5.1 show that $p = 0 - 1$ for $\tau^*/\tau_{cr}^* = 0.07 - 0.7$, respectively. It may therefore be inferred from this result that particle entrainment from the cavity reaches 100% at τ^* values which are 30% lower than the critical values (τ_{cr}^*) computed using the Shields' diagram. This is an interesting aspect to observe, that particle entrainment from a rectangular cavity whose depth is several times the particle diameter, can take place at considerably lower values of τ^* than that required for entrainment on a flat sediment bed. This phenomenon can be explained if we recognize that flow regime inside the cavity is much more turbulent than that in the free-stream region, and the additional energy required by a particle to jump over the cavity depth (D) is being supplied by the higher turbulence that exists within the rectangular cavity.

Figure 5.1 Entrainment probability (p) vs. τ^*/τ_{cr}^* and $\tau^*/\tau_{cr-sumer}^*$

The experimental τ^* values are also compared with the critical values proposed by Sumer et al. (2001) in Fig. 5.1. Sumer et al.'s (2001) work is the closest to the present study amongst all the particle entrainment studies the author could find in published literature. Sumer et al. (2001) studied particle entrainments from cavities, which are gaps in between stones, and proposed Eqn. 5.2 using the ratio of the stone size and particle diameter. Here, the stone size is analogous to the cavity depth (D) that the particle has to jump over in order to be successfully entrained. Accordingly, the $\tau_{cr-sumer}^*$ values are presented in Table 5.3 and the entrainment probabilities are plotted with respect to $\tau^*/\tau_{cr-sumer}^*$ in Fig. 5.1. However, it must be noted that the present study uses a much deeper and larger cavity in comparison with the "cavity" in Sumer et al. (2001). Fig. 5.1 shows that $p = 0 - 1$ for $\tau^*/\tau_{cr-sumer}^* = 0.0014 - 0.028$, respectively. Based on the data, it is interesting to note that particle entrainment from a rectangular cavity is easier than from a small gap, most likely because of the higher turbulence near the cavity downstream edge in the former case. Another reason can be the 'shielding' or 'hiding' effect experienced by a sediment particle surrounded by other particles, as in the case with the study of Sumer et al. (2001).

The variability in particle entrainment as evidenced from the entrainment probability (p) values and Fig. 5.1 is due to the randomness in the turbulent flow field prevalent inside the cavity. Additionally, entrainment occurring at considerably low values of Shields parameter compared to other studies as seen in Fig. 5.1 can also be attributed to higher turbulence and presence of eddies in the cavity when compared to that in the free-stream flow region. Hence, in order to visualize the flow inside the cavity, PIV is used and the results are discussed in the succeeding section.

However, before proceeding further, it is important to state that as mentioned in Chapter 4, the entrainment probability (p) values in Table 5.3 also share the same 95% confidence intervals as per Eqn. 4.7. Moreover, the entrainment time distributions in this test series best fits the lognormal PDF as in the test series of Chapter 4 (refer to Fig. 4.8). Furthermore, the particle trajectories in this Series 2 test runs mostly follow the Stage 02 category of trajectories (refer Fig. 4.9 b). The particles show high spanwise movements along the cavity downstream edge, and no upstream movements at all, with more entrainments occurring

from the cavity downstream corners than from the cavity downstream edge center. The reasons for this will become clearer when the PIV results are introduced and discussed in the next section.

5.3 Free-stream flow field vs. cavity flow field: PIV results

PIV is used in this study to capture the flow field in the free-stream region and inside the rectangular cavity as well. In order to help relate the flow field measured in different regions in the test set-up, a simple illustrative sketch of the coordinate system and measurement planes is shown in Fig. 5.2. This sketch is in addition to the detailed experimental set-up sketch already presented in Ch-3.

Figure 5.2 Illustrative sketch of coordinate system and PIV measurement planes ($L = 100$ cm, $D = 5.3$ cm; not to scale)

The free-stream region is measured around $x = -1$ m upstream of the cavity leading edge (or 8 m downstream of the flume entrance) along the flume streamwise centerline i.e. $z = 24.5$ cm. The free-stream flow field is compared to the flow field inside the cavity near the cavity downstream edge at $z = 24.5$ cm (plane 01 or PL01), and at $z = 1$ cm from the side wall (plane 02 or PL02). The flow field inside the cavity is assumed to be symmetrical along the

streamwise centerline, and hence the flow field recorded at $z = 1$ cm is also applicable to $z = 48$ cm near the opposite cavity corner.

The PIV tests are conducted under 3 different free-stream velocities $u = 0.26$ m/s, 0.285 m/s and 0.322 m/s. Please refer to Ch-3 for the detailed PIV set-up and processing methodology, and Table 5.1 for details of the flow configurations. For these 3 flow conditions used in the PIV measurements, it is observed that apart from the expected quantitative increase in the flow and turbulence parameters with increasing u , there are no other qualitative differences in these 3 flow fields. Hence, to avoid clutter but remain consistent, all flow fields discussed in this chapter are the ones corresponding to the flow configuration with $u = 0.26$ m/s.

Fig. 5.3 shows the streamlines of the time-averaged flow field in the (a) free-stream region; (b) center-plane near the cavity downstream edge at $z = 24.5$ cm (PL01); and (c) the plane near the side-wall at $z = 1$ cm (PL02). In the figure, $|V|$ denotes the velocity magnitude $= \sqrt{V_x^2 + V_y^2}$. It is seen that the averaged free-stream flow field (Fig. 5.3 a) is uniform with essentially straight horizontal streamlines throughout the flow depth. However, this is not the case inside the cavity; the flow fields in PL01 and PL02 (Figs. 5.3b and c) are highly non-uniformly distributed, especially near the downstream cavity edge where most of the particles were observed to be present before their eventual entrainment. Besides this, the experimental data also show that the velocity magnitude generally is lower in PL01 and PL02 when compared to that in the free-stream region. In PL01, there is also the formation of a well-defined and pronounced clockwise rotating recirculation vortex adjacent to the cavity downstream edge, which likely is responsible in preventing the particle from coming in close proximity to the cavity edge. However, no such distinct recirculation vortex is observed in the data of PL02, although upstream moving flow near the edge is present.

Figure 5.3 Streamlines of time-averaged XY flow field in: (a) free-stream region; (b) downstream central cavity plane PL01; (c) downstream corner cavity plane PL02

Furthermore, although the velocity magnitude is lower in both PL01 and PL02 compared to the free-stream region, there is an obvious upward moving flow near the cavity downstream edge, which acts to help the particles to be entrained from the cavity. In contrast, the free-stream region has no discernible upward moving flow and a particle has to solely depend on the random velocity fluctuations for entrainment. On the other hand, when compared to a particle on a flat bed, a particle inside the cavity, faces a bigger challenge for entrainment because it has to overcome a potential energy equivalent to D , which is several times its diameter. However, its entrainment is helped by the upward moving flow near the cavity edge which is non-existent on flat beds. This flow non-uniformity near the cavity downstream edge and the absence of any ‘shielding’ of the particle in the cavity, are the reasons why we see in Fig. 5.1 that the entrainment probability (p) can reach 1.0 at considerably low critical Shields parameter (τ_c^*), a value that is needed for particle entrainments on a flat sediment bed.

The differences in the magnitude of the streamwise (V_x) and vertical velocity (V_y) in different flow regions becomes apparent in Fig. 5.4 where the time-averaged and space-averaged velocity profiles are plotted for the free-stream region, and the 2 planes inside the cavity - PL01 and PL02. For PL01 and PL02, the velocity is space averaged at intervals of $x = 1.5$ mm between 25 to 35 mm upstream from the cavity trailing edge. Fig. 5.4 (a) shows the streamwise velocity profiles: the logarithmic law of the wall in the free-stream region, and the comparatively lower V_x in planes PL01 and PL02. A slightly negative V_x (moving upstream) is also detected near the cavity bed for PL02. No negative V_x , however, is observed in the PL01 profile despite the presence of the clockwise recirculation vortex, because the velocity is averaged over the location that is confined to 25-35 mm upstream of the edge of the rectangular cavity and is beyond the recirculation vortex's location in PL01. In contrast, in PL02, the upstream moving flow exists all the way to 50 mm from the edge (please refer to Fig. 5.3 (b) and (c) for better understanding). Although the streamwise velocity, V_x inside the cavity is lower in magnitude than in the free-stream region, Fig. 5.4 (b) reveals the significantly higher V_y inside the cavity in both PL01 and PL02. V_y is the highest in PL02, followed by in PL01 and negligible in the free-stream region. The V_y

profiles in PL01 and PL02 follow a skewed parabolic shape with the maxima occurring at just above the cavity top, and minima occurring both at the cavity bed and at the free surface. The velocity magnitudes thus follow the following order:

Figure 5.4 Time-averaged and space-averaged velocity profiles in the free-stream region, PL01 and PL02 (a) streamwise velocity, V_x (b) vertical velocity, V_y

$$V_x \text{ (free-stream region)} > V_x \text{ (cavity plane: PL01)} > V_x \text{ (cavity plane: PL02)}$$

$$V_y \text{ (free-stream region)} \ll V_y \text{ (cavity plane: PL01)} < V_y \text{ (cavity plane: PL02)}$$

The effect of V_y on particle entrainment is also noticed during experimental observations of frequent occurrences of entrainment from the downstream corner of the cavity (PL02), which has the highest V_y , rather than from the center of the cavity (PL01) which has lower V_y when compared to PL02.

The averaged-flow streamlines in Fig. 5.3 are complemented by their corresponding turbulent kinetic energy (TKE) plots in Fig. 5.5 for all the 3 planes. The TKE plots shown here use only the streamwise velocity fluctuations (V'_x) and the vertical velocity fluctuations (V'_y) such that $\text{TKE} = 0.5 \left(\overline{V'^2_x} + \overline{V'^2_y} \right)$. Fig 5.5 shows a significant difference between the TKE in the free-stream region and those near the cavity downstream edge. The region near the cavity edge with the highest TKE is also the region in which most of the particle entrainment takes place. Although, PL01 has somewhat higher TKE than the sidewall plane PL02, the more frequent particle entrainments having occurred along PL02 suggest that the higher V_y and absence of the well-defined recirculation vortex in PL02 (when compared to PL01) may have contributed to the entrainment process. Additionally, more entrainment events close to the sidewall with respect to the symmetry plane, may also be because of the spanwise (time-averaged) velocity diverging from the symmetry plane, and moving particles in the proximity of the wall.

The higher TKE in PL01 and PL02 also implies higher variability in the velocity fluctuations near the cavity downstream edge, hence making the flow more turbulent. Thus, the instantaneous values appear to have played a more deciding role in the entrainment process than the averaged parameters. Only if the instantaneous fluid force is high enough can a particle be pushed into the high TKE region for an eventual successful entrainment.

Figure 5.5 Contours of turbulent kinetic energy (TKE) in the (a) free-stream region; (b) downstream central cavity plane PL01; (c) downstream corner cavity plane PL02

The instantaneous-flow streamlines, which are plotted in Fig. 5.6 are compared to the time-averaged-flow streamlines seen in Fig. 5.3. Fig. 5.6 (a) shows that the streamlines in the free-stream region are mostly the same, be it the time-averaged flow or the instantaneous flow. However, there are significant variations between the streamlines for the instantaneous flow field and time-averaged flow for PL01 and PL02, with more non-uniformities seen at the cavity corner (compare Figs. 5.6b with 5.6c). Some random instantaneous small-scale vortices are also present at the cavity bottom close to the downstream edge in PL02 and PL03, where most of the particle entrainments commence from. Hence we can deduce from Figs. 5.3 - 5.6 that the instantaneous flow fields are primarily responsible for the stochastic entrainment process. In order to overcome the cavity depth, an entrainment is favored by the high TKE region, upward moving flow near the cavity edge, and random fluctuations, which may be the most influential and definitive factor in putting the particle in a favorable flow condition leading to a successful entrainment.

Fig. 4.9 in Ch-4 exhibited a lot of spanwise movements in the particle trajectories along the cavity downstream edge. This is also observed in the data presented in this chapter, where the particles confined themselves to the Stage 02 trajectories. To investigate further, PIV is used to capture the spanwise flow velocity (V_z) along the downstream edge - PL03 (see Fig. 5.2). Fig. 5.7 (a) shows the time-averaged spanwise flow 1 cm upstream of the cavity trailing edge where fixed alternate regions of positive and negative V_z are present. However, plan-view particle trajectories in Fig. 4.9 reveal that particles first reach the center of the downstream edge, before moving spanwise to either of the two cavity corners. Sometimes, they also move from one corner to the opposite one. The presence of fixed alternate regions of V_z does not explain this particle movement convincingly. Although the time-averaged transverse velocity plot in Fig. 5.7 (a) shows a defined negative-positive-negative pattern from $z = 250 - 10$ mm, the instantaneous pattern can be significantly different, and occasionally completely contrary to the mean pattern, as seen in the instantaneous spanwise flow fields plotted in Fig. 5.7 (b), (c), (d) at three different time instants. These instantaneous fields show that the regions of positive and negative V_z are not constant in space and time but rather unsteady and keep changing along the downstream edge of the cavity. In Fig 5.7

Figure 5.6 Streamlines of the instantaneous XY flow field in the (a) free-stream region; (b) downstream central cavity plane PL01; (c) downstream corner cavity plane PL02

(a), the spanwise area from the cavity center $z = 250$ mm to $z = 10$ is divided into 3 regions of negative, positive, and negative V_z whereas in (b) it is completely negative, in (c) it reverts to negative-positive-negative pattern and in (d) it becomes negative-positive-negative-positive, with negative V_z towards the cavity corner. These areas with alternating directions of V_z explain the random to and fro transverse movements of the particle along the cavity downstream edge seen previously in Fig. 4.9. This random changes of the velocity pattern along the downstream edge of the cavity accounts for particle entrainments that sometimes

Figure 5.7 Contours of spanwise velocity (V_z) in the cavity plane PL03: (a) time-averaged contours; (b), (c), (d) contours at different time instants

occur at the center (PL01), sometimes at the corner (PL02) and at other times from anywhere in between.

This variation is also seen in the vertical velocity (V_y) plots along the spanwise plane in Fig. 5.8 with the time-averaged flow field shown in (a) and the instantaneous ones in (b), (c) and (d). However, the cavity edge is predominantly divided into two regions - upper region with an upward moving velocity, and a smaller lower region with downward moving velocities. Hence, a particle resting on the bed has to overcome this negative V_y region initially before it can be entrained from the cavity.

Figure 5.8 Contours of vertical velocity (V_y) in the cavity plane PL03: (a) time-averaged contours; (b), (c), (d) contours at different time instants

Thus, the PIV results at the 3 planes (PL01 – PL03) give us a clearer picture of why the entrainments are occurring from different regions and under what circumstances are they more likely to be entrained. The flow fields also highlight the contrast between the steady unidirectional uniform flow in the free-stream region and the highly unsteady, multi-directional flow inside the cavity. The instantaneous flow fields in the cavity show large variations from their time-averaged counterparts. This explains why the entrainment process is probabilistic and not deterministic. The higher randomness in the cavity flow field compared to that in the free-stream region is also highlighted in the TKE plots, in which the TKE in the PL01 and PL02 locations is higher despite having lower $|V|$. It is this randomness that is mainly responsible for the stochastic aspects of the entrainment process, and is what makes particle entrainment from a cavity so much different from that on a flat bed. The transverse movement in the particle trajectories is also explained by the shifting positive and negative V_z fields in the spanwise plane along the cavity downstream edge. In the next section, entrainment of particles is analyzed in greater details with the help of the results from PIV measurements.

5.4 PIV analysis of an entraining particle

In the previous chapter, the plan view trajectories (in the XZ plane) plotted in Fig. 4.9, showed the particle trajectories from their release position at the cavity center ($x = 0.5$ m, $z = 0.245$ m) until their entrainment from the cavity downstream edge or their motion to the upstream region of the cavity. A part of this complete entrainment process - the lifting of the particle from the cavity bed, and its ensuing motion to the cavity top is discussed in details in this section. This initial lift off and subsequent entrainment is recorded using PIV near the cavity trailing edge in the XY plane close to the cavity side wall. Here, lift-off refers to the initial upward movement of the particle resting on the bed to just above the bed; which is then followed by an upward motion finally leading to entrainment from the cavity. It must be stated that based on this definition, a lift-off does not guarantee an entrainment.

On the cavity bed, the particle may move freely in the streamwise (X) and spanwise (Z) directions as seen in the plan-view trajectories. Hence a proper plane has to be chosen where the particle experiences minimal spanwise (Z) deviation so as to keep the particle in the PIV laser plane during the lift off and entrainment process. The plane along the cavity centerline ($z = 0.245$ m) was found to be unacceptable for this purpose because of significant spanwise movement of the particle near this plane. Hence, the XY plane at $z = 0.005$ m near the cavity corner is chosen for recording this lifting motion as it showed less spanwise movements, thus reducing the odds of the particle straying away from the laser plane. Also, it should be stated that although a lot of such particle entrainments were recorded during the experiments, only the ones which stayed in the laser plane during $> 90\%$ of the recording duration are presented and discussed here.

Figs. 5.9 (a), (b), (c), (d) show several of the XY trajectories during the lift-off and entrainment phase. The particle coordinates are extracted from the recorded video using the tracking code developed by Hedrick (2008). Although only four trajectories are plotted here, these are fairly representative of all the trajectories recorded during the experiments.

From the four trajectories presented here, it is clear that all the particles are entrained close to the separation line of the downstream backflow (refer Fig. 5.3 b, c) which is also a zone of higher turbulence, due to the instability of the structure (refer to Fig. 5.5 b, c), with lift-off from the cavity bottom initiating around 20-40 mm upstream of the cavity edge and the particle reaching the cavity top following an arc shaped trajectory. However, the trajectories clearly are not smooth but undergo significant perturbations throughout their journey from the cavity bed to the cavity top. It must be noted that the particles need to cover as much as 4 - 9 times their diameter (d) for a successful entrainment in these entrainment events. This is in contrast to studies in the past where entrainment is equated to particle dislodgement of 1 times the diameter and even less. In the case of such small displacement entrainments, a critical impulse criterion is appropriately adopted and the effect of a continuously changing flow field on the particle motion is appropriately ignored because of the small trajectory length and an equally small duration needed for such an entrainment. This critical impulse concept for small displacements has been studied by Valyrakis et al. (2010), Celik et al.

Figure 5.9 Representative particle trajectories in the XY plane at the time of entrainment from the rectangular cavity

(2013), Diplas and Dancey (2013) and others, and an illustration of this process is provided in Fig. 5.10. The figure shows sediment particles stacked on a bed where entrainment is equated to lifting of the particle (marked in red-dashed line) from 'O' to 'A', which is approximately equal to its diameter. This small movement is modeled as the result of an impulse acting on the particle for a very small duration of $T \ll t_{OA}$ as seen in the inset of Fig. 5.10. Taking into account that these previous studies are conducted in flow conditions

similar to the free- stream region in the present study where the flow field is essentially unidirectional, steady and uniform, a small impulse may be considered sufficient for the particle to be entrained for a distance equal to its diameter. However, when this type of flow field is compared to the 3-dimensional unsteady flow field near the cavity downstream edge (please refer Figs. 5.3 - 5.8) with streamlines and vortices undergoing significant and intermittent changes; a particle that needs to overcome a potential energy equivalent to several times its diameter in such a fluctuating flow field may not be adequately represented by a one-time critical impulse framework (where an impulse acts on the particle only once at the cavity bed and no more later on). In fact, the particle in the present study, upon receiving a high impulse, may even be brought down by the instantaneous flow field before it reaches the cavity top. In other words, the particle needs a continuous stream of instantaneous forces, or multiple impulses at different stages of its upward motion, to help it to be entrained from the cavity.

Figure 5.10 Critical impulse concept used for particle dislodgement or entrainment of 1 diameter in a steady uniform flow regime (Reproduced from Valyrakis et al., 2010)

This hypothesis is attested by the trajectories in Fig. 5.9, which shows that a particle entrainment can be considered to be in multiple stages with, perhaps an impulse initiating the initial upward motion, followed by the instantaneous flow field shaping and sustaining the entire progress of the particle until its eventual entrainment from the cavity. The trajectories can be better understood when seen in conjunction with the average and instantaneous streamlines plotted in Fig. 5.3 (c) and Fig. 5.5 (c). The particle is not just moving up continuously, but is sometimes falling down slightly, before being pushed up and being entrained eventually. Hence, this entrainment from a cavity is depending on a multitude of instantaneous forces acting on the particle, simultaneously from different directions or in succession, and affecting its entrainment trajectory, and its entrainment probability (p).

In the following discussion on the entrainment mechanism, the trajectory in Fig 5.9 (a) is singled out for scrutiny, in which the particle is SP5 ($d = 0.78$ cm, $\rho_s = 1.1$ g/cc), the free-stream velocity (u) = 0.26 m/s and cavity depth (D) = 53 mm. Nevertheless, observations and results for this particle are applicable to all the other trajectories and the general entrainment phenomenon. The unsteadiness and perturbations in the particle trajectory can also be visualized by the time series of the particle's velocity ($v_{x,p}, v_{y,p}$) and acceleration ($a_{x,p}, a_{y,p}$), plotted in Fig. 5.11 for the trajectory in Fig. 5.9 (a). All the time series in Fig. 5.11 are plotted for the entire path shown in Fig. 5.9 (a), and time = 0 in the x-axis corresponds to the particle position 'A' in Fig. 5.9 (a). The particle takes ≈ 1.4 seconds to move from position 'A' on the cavity bed to position 'F' near the cavity top. The particle velocity and acceleration values are obtained by numerical differentiation of the particle coordinates using the 3-point central difference formula. Under a one-time critical impulse framework, the particle velocity would have been constantly decreasing since no other fluid force is considered after the impulse has acted on the particle. However, Fig. 5.11 (a) shows how the particle velocity in both the streamwise and the vertical direction is constantly changing in magnitude and direction, and reaching the maximum velocity only at the end of the trajectory at position 'F' when the particle is close to the cavity top. The acceleration time series further substantiates the instantaneous changes in the particle trajectory with

values wildly fluctuating within the range of -3 m/s^2 to 3 m/s^2 in both the streamwise and vertical direction.

Figure 5.11 Time series of (a) particle velocity, and (b) acceleration, for the particle trajectory shown in Fig. 5.9 (a)

With the particle undergoing such swift changes in position, velocity and acceleration within a short duration of ≈ 1.4 sec along its trajectory, it is imperative to examine the instantaneous flow field around the particle during this entrainment phase. Accordingly, some snapshots of the instantaneous velocity vectors surrounding the particle are presented in Fig. 5.12. These snapshots correspond to different time instants in the particle's entrainment trajectory, and the particle position is made identifiable by drawing a white square box around it. The snapshots also show the flow velocity magnitude $|V|$ as colored contours. The instantaneous vector fields in Fig. 5.12 correspond to the particle locations A - F marked in Fig. 5.9 (a). An animation of this entire process can also be accessed via web link² for a better visualization of the flow vectors surrounding the particle during this entrainment process.

Fig. 5.12 (a) shows the vector field when the particle is at position A, just before the initial lift off from the cavity floor. The instantaneous vectors above the particle are pointed upwards in +Y direction and have comparatively higher magnitude (shown by the red and yellow contours) than that of the other vectors (lower magnitude is indicated by the blue contours) surrounding the particle. This difference in magnitude between the velocity vectors in different flow regions leads to a pressure difference with an upward bias around the particle, which in turn initiates the particle lift-off from the cavity bed.

From position A, the particle that has just been lifted off from the bed, moves a small horizontal and vertical distance before reaching position B. At this juncture, the velocity vectors over the particle are now pointing in a direction opposite to the one it had previously been subjected to. The instantaneous vector field for position B is shown in Fig. 5.12 (b). At B, the particle changes course from +X to -X (towards position C) although the vertical direction is still upwards (+Y). This change in direction from +X to -X at B is accompanied with the particle rotating during this transition, which can be readily perceived if one refers to the animation mentioned above. This change in trajectory direction is influenced by the higher magnitude velocity vectors that are present at the top left corner of the particle (red contours).

² <https://www.dropbox.com/s/55a79rznwbcxc2s/ch5%20Particle%20entrainment%20-%20close%20to%20cavity%20edge.gif?dl=0>
shortened url: <https://tinyurl.com/glvy6z>

Figure 5.12 Flow field around particle at different positions and time instants in its entrainment trajectory: (a) position A; (b) position B; (c) position C; (d) position D; (e) position E; (f) position F.

From position B, the particle moves in the same direction until it reaches C, covering a distance of $x \approx -10$ mm and $y \approx +3$ mm. This movement from B to C is also accompanied with the particle rotating, before changing course again at C. The velocity vector field for position C is depicted in Fig. 5.12 (c), which clearly shows that the velocities surrounding the particle have decreased in magnitude (blue colored contours). This reduction causes the particle to lose its momentum and it dips slightly. However the dip is temporary and the particle again starts moving in a near horizontal line along the streamwise direction (+X) before changing direction and travelling upwards (+Y) to reach position D.

At position D (Fig. 5.12(d)), all the vectors around the particle can be seen to be pointing upwards. This position is an intermediate one between C and E with the maximum vertical distance travelled by the particle, although not in a perfect straight line. The particle's upward motion is also evident by the velocity vectors present over the particle which too are pointed in the upward (+Y) direction.

From D to E, the particle covers a vertical (upward) distance of ≈ 20 mm. However, this includes a direct upward movement, followed by motion in the +X direction, and then a -X diagonal upward movement to reach E. While at E, the immediate region around the particle has distinctly lower velocity magnitude as evident by all the blue contours in Fig. 5.12 (e). This instantaneous reduction in the flow velocity and the particle's momentum, again leads to another temporary dip in the Y direction after the particle has reached position E.

At E, the particle is already very close to the cavity top, just ≈ 18 mm away from being finally entrained. The upward motion from E to F is swifter than previously experienced due to the higher flow velocity (V_y) near the cavity top. The instantaneous field for F is shown in Fig. 5.12 (f). At F, the particle has already covered a vertical distance higher than the cavity depth, and is just few milliseconds away from crossing the cavity downstream edge. The final entrainment is easily effected by the high streamwise velocity and TKE at this location.

In summary, one can infer from Figs. 5.12 (a) - (f) that within the short duration of 1.4 seconds, the particle has travelled a net upward vertical distance of 6.8 times the particle

diameter ($d = 0.78$, $D = 53$ mm) to be successfully entrained from the cavity. However, the trajectory is not a perfectly straight line; in other words, the total distance travelled exceeds the cavity depth, $D = 53$ mm. Instead, the particle changes its course multiple times in the +X, -X, +Y, and -Y directions, until it is finally entrained from the cavity. This is due to the turbulent flow field that constantly changes from one instant to another, causing the particle to change direction, lose momentum, dip downwards and resume again, before eventually escaping from the cavity.

Whereas in previous studies on particle entrainment on a flat bed, the initial liftoff at A would have been enough to effect an entrainment (Valyrakis et al, 2010), in the present study, it is seen that the momentum gained by the particle during lift off at A is not sustained all the way till F. The momentum either dies out at B or the instantaneous flow field at B acts contrary to the particle motion, reducing the particle's momentum and causing the particle to change course altogether. This change in direction is not limited to just at position B, but is witnessed throughout the trajectory: once at B, once at C, once between C and D, twice between D to E, and twice between E to F (please refer Fig. 5.9 (a)). This particle trajectory and the associated instantaneous flow fields bring out the randomness in the cavity flow field, and shows that even a high impulse at A may not be enough for entrainment as it is also dependent on the instantaneous flow fields between A to F to sustain the particle momentum until entrainment. On the other hand, a series of small impulses at various stages can lead to a successful entrainment as it is likely the case for the particle in Fig. 5.9 (a). However, high impulses at the cavity bed may lead to entrainment probably in cases of Figs. 5.9 (b), (c) and (d) where trajectories are less crooked although they are by no means straight lines; these too have their peculiar perturbations and idiosyncrasies all the way until the cavity top. Finally, the particle velocity is also not constant nor is it constantly increasing or decreasing as apparent from Fig. 5.11 (a); instead, the particle undergoes random movements during its upward motion to reach the cavity top.

All these trajectories, time series and instantaneous flow fields reflect the fact that particle entrainment from a cavity is much more complex than that on a flat bed. This is partly due to the longer distance that a particle has to travel upwards (at least equal to the cavity depth), the longer duration that is needed to cover this distance, and the widely varying

instantaneous flow fields that the particle is subjected to during this period, which can significantly affect the trajectory in numerous ways. The discussion highlights the multi-stage process involved in a successful entrainment, in which the particle is subjected to a constantly changing flow field around it; and which, in turn, imparts the entrainment phenomenon its stochastic nature.

5.5 Summary

Particle entrainment experiments from a rectangular cavity are carried out at different free-stream velocities (u) for different particles under a fixed cavity configuration: $L = 100$ cm, $D = 5.3$ cm. PIV measurements are conducted in the free-stream region as well as inside the cavity to compare the flow fields in the two cases, and to study a particle's upward motion during a successful entrainment process. The entrainment probability is plotted with respect to the ratio of experimental τ^* to critical dimensionless shear stress (τ^*) computed using the Shields diagram and Sumer et al.'s (2001) study. The data show that 100% particle entrainment from the cavity is achieved at 0.7 times the critical dimensionless shear stress computed using the customary Shields diagram, and at 0.028 times the critical Shields parameter proposed by Sumer et al. (2001). It must be noted that the experimental τ^* values are computed with the free-stream u_* . It is interesting to compare the results for entrainment from large shallow cavities (present study), from flat sediment beds (Shields (1936)), and from small deep cavities (Sumer et al. (2001)). The 100% entrainment at low τ^* compared to previous studies highlight the fact that although higher energy is required by the particle to jump above the cavity height, this extra energy is more than adequately provided for by the turbulent flow field inside the cavity. This is also substantiated from the flow fields in Fig. 5.3 - 5.6 where the average and instantaneous streamlines, and TKE at the free-stream region and the cavity region are compared. The plan-view particle trajectories in these test runs fall under the stage 02 category seen in Fig. 4.9, and the entrainment time distributions fit the same lognormal distribution as seen in Fig. 4.8 in Ch-4.

The flow fields obtained from PIV measurements reveal the unsteadiness and multidirectionality in the cavity flow compared to the steady, uniform and unidirectional flow in the free-stream region. From Figs. 5.3 - 5.5, it can be deduced that although the streamwise velocity near the cavity downstream edge is lower compared to that in the free-stream region, the vertical velocity and turbulence is significantly higher near the cavity edge. The randomness inside the cavity is also highlighted by the instantaneous flow fields plotted in Fig. 5.6 with irregular small-scale vortices abounding near the cavity bed close to the downstream cavity edge. The time-averaged and instantaneous flow fields in Figs. 5.7 and 5.8 show the unsteady and alternating regions of positive and negative spanwise velocity existing near the cavity downstream edge and helps explain the random to and fro particle movements in the spanwise direction as seen in the plan-view (XZ) particle trajectories of Fig. 4.9 in Ch-4.

The descriptions of the cavity flow fields in section 5.3 is followed by discussion of the particle trajectories in the XY plane (i.e. side view of the lift-off and entrainment process). It is seen that the particle path is not a smooth trajectory but has significant streamwise and vertical movements throughout. The velocity and acceleration time series combine to show that the particle undergoes severe changes in its trajectory due to the instantaneous flow field. This fluctuating particle velocity points to the fact that the particle movement is under the influence of different forces in different stages of its trajectory. This is because, if only a single impulse had acted at its lift-off from the cavity bed and no subsequent forces are present thereafter, the particle velocity would have been continuously decreasing as it approaches the cavity top rather than seen fluctuating throughout the time series, as is shown in Fig. 5.11. The higher influence that the instantaneous flow field has on the particle is due to the longer distance the particle is travelling before a successful entrainment is completed and the longer time that is required to cover this distance, leaving the particle completely dependent on the constantly changing flow field around it, as is seen in Fig. 5.12. An animation of the instantaneous flow field around the particle just prior to lift-off from the cavity bed right till its entrainment from the cavity is also provided as a web link in section 5.4.

In summary, this chapter shows how the instantaneous flow field near the cavity downstream edge is constantly influencing the particle throughout its trajectory, thus making the particle entrainment process a highly probabilistic phenomenon. In the next chapter, the effect of cavity geometrical parameters on the particle entrainment probability (p) is discussed even when the cavity aspect ratio (L/D) is kept unchanged, and results are compared with those presented in Ch-4 using the flow field data obtained from the PIV measurements.

Chapter 6

Effect of cavity geometrical parameters on particle entrainment and related cavity flow field

6.1 Introduction

In Chapter-4, particle entrainment from a cavity was studied under a wide range of cavity depth (D), with the cavity length (L) being held constant throughout (Series 1). However, the cavity length (L) can also significantly alter the flow field inside the cavity, and in turn, affect the entrainment probability (p) in multiple ways. Hence, another series of experiments (Series 3) is carried out with varying L and constant D , and the results compared with those obtained from Series 1, so as to better understand the effect of the cavity geometry on particle entrainment as a whole. This chapter, thus examines the effect of both L and D in a more integrated manner using entrainment probability results and PIV measurements of the cavity flow field corresponding to the data presented in Ch-4, i.e. Series 1 and the current experiment set, i.e. Series 3.

6.2 Entrainment probability as a function of cavity geometrical parameters

Past research studies on rectangular cavity flows without any consideration on particle entrainment, has always used the cavity aspect ratio L/D to characterize the flow field inside the cavity. Some of these studies conducted with low cavity aspect ratios ($L/D < 5$) are those of Faure et al. (2007), Haigermoser et al. (2008), Mori and Naganuma (2009), Silva et al. (2012), Cicca et al. (2013), Fernando et al. (2013) and others. Research on shallow cavities with high aspect ratios ($L/D \geq 10$) have also been carried out and reported in studies by Esteve et al. (2000), Reulet et al. (2002), Zidanski et al. (2008), Madi

Arous et al. (2011) and others. It is implicitly assumed in these studies that the cavity length to depth ratio (L/D) can be used to demarcate the type of flow field in the cavity.

In this context, it is imperative to check whether L/D can also be used for characterizing particle entrainment from a rectangular cavity. Accordingly, the new test Series 3 is conducted with fixed D and varying L such that the aspect ratio in Series 3 replicates those in Series 1. In Series 1, L was fixed at 1000 mm and D was varied from 10 mm - 113 mm, yielding $L/D = 8.9 - 100$. In Series 3, D is fixed at 50 mm and L is varied from 443 mm - 945 mm giving a range of L/D from 8.9 - 18.9. Consequently, the results from both Series 1 and Series 3 with aspect ratios = 8.9 - 18.9 are compared in the present chapter.

All the cavity configurations and the associated entrainment probabilities are listed in Table 6.1 where L, D, H represents the cavity length, cavity depth, and the total flow depth at the cavity. Series 3 is conducted under the same free-stream flow conditions as Series 1 (flow configuration F1) where the free-stream velocity (u) 1 m upstream of the cavity leading edge is 0.26 cm/s and the free-stream flow depth outside the cavity is 0.12 m. For more details of this flow condition, please refer Table 4.1. The 4 particles used in this Series 3 are SP2, SP4, SP5 and SP6 and their properties can be found from previous chapters in Table 4.2 or Table 5.2.

As in Series 1 and 2, the observation duration and the total number of trials for each cavity configuration are fixed at 2 minutes and 50 trials, respectively. Furthermore, in order to better scrutinize the particle behavior under different cavity configurations, two more probabilities are listed in Table 6.1 apart from the already discussed entrainment probability (p) = ratio of successful entrainments to the total number of trials i.e. 50. These two new probabilities are (1) downstream probability (p_{ds}) = number of particles moving to the cavity downstream edge after their release from the cavity center divided by the total number of trials i.e. 50; and (2) intermediate probability ($p_{et/ds}$) which is the ratio of

Table 6.1 Experimental data for Series 1: varying cavity depth (D), and Series 3: varying cavity length (L) under same free-stream flow conditions

Particle Type	Series #	L (mm)	D (mm)	H (mm)	L/D	D/H	p_{ds}	$p_{et/ds}$	p
SP2	1	1000	113	233	8.9	0.48	0	-	0
			101	221	9.9	0.46	0.04	-	0.04
			89	209	11.2	0.43	0.24	1	0.24
			81	201	12.4	0.40	0.64	0.97	0.62
			77	197	13	0.39	0.94	1	0.94
			65	185	15.4	0.35	1	1	1
			53	173	18.9	0.31	1	1	1
	3	443	50	170	8.9	0.29	0.02	-	0.02
		495			9.9		0.14	-	0.14
		562			11.2		0.48	1	0.48
		618			12.4		0.72	1	0.72
		650			13		0.88	1	0.88
		769			15.4		1	1	1
		945			18.9		1	1	1
SP4	1	1000	113	233	8.9	0.48	0	-	0
			101	221	9.9	0.46	0.06	-	0.06
			89	209	11.2	0.43	0.26	1	0.26
			81	201	12.4	0.40	0.54	1	0.54
			77	197	13	0.39	0.92	0.98	0.9
			65	185	15.4	0.35	1	1	1
			53	173	18.9	0.31	1	1	1
	3	443	50	170	8.9	0.29	0	-	0
		495			9.9		0.1	-	0.1
		562			11.2		0.48	1	0.48
		618			12.4		0.7	1	0.7
		650			13		0.94	1	0.94
		769			15.4		1	1	1
		945			18.9		1	1	1

(Contd).

(Contd).

Particle Type	Series #	L (mm)	D (mm)	H (mm)	L/D	D/H	p_{ds}	$p_{et/ds}$	p
SP5	1	1000	113	233	8.9	0.48	0	-	0
			101	221	9.9	0.46	0.08	-	0.06
			89	209	11.2	0.43	0.16	-	0.12
			81	201	12.4	0.40	0.48	0.83	0.4
			77	197	13	0.39	0.94	0.87	0.82
			65	185	15.4	0.35	1	0.94	0.94
			53	173	18.9	0.31	1	0.92	0.92
	3	443	50	170	8.9	0.29	0	-	0
		495			9.9		0.12	-	0.12
		562			11.2		0.46	0.83	0.38
		618			12.4		0.68	0.88	0.6
		650			13		0.94	0.89	0.84
		769			15.4		1	0.92	0.92
		945			18.9		1	0.94	0.94
SP6	1	1000	113	233	8.9	0.48	0	-	0
			101	221	9.9	0.46	0.06	-	0
			89	209	11.2	0.43	0.12	-	0
			81	201	12.4	0.40	0.56	0.14	0.08
			77	197	13	0.39	0.94	0.17	0.16
			65	185	15.4	0.35	1	0.32	0.32
			53	173	18.9	0.31	1	0.48	0.48
	3	443	50	170	8.9	0.29	0	-	0
		495			9.9		0.04	-	0.02
		562			11.2		0.58	0.34	0.2
		618			12.4		0.74	0.3	0.22
		650			13		0.86	0.3	0.26
		769			15.4		1	0.4	0.4
		945			18.9		1	0.44	0.44

successful entrainments to the number of particles that have moved downstream. Thus, we can see that entrainment probability (p) is a product of these two new probabilities, i.e. $p = p_{ds} * p_{et/ds}$. These two new probabilities help segregate the number of particles moving downstream or upstream from the cavity center, and also separate the number of successful entrainments amongst the downstream moving particles. This is done because for a successful entrainment, the particle must first travel to the cavity downstream edge, and knowing this downstream probability is useful in cases where some particles move downstream, and others upstream in the cavity, the latter leading to zero entrainment. It must also be stated that for any cavity configuration, when the number of particles moving downstream is <10 out of the 50 trials, the $p_{et/ds}$ values are ignored so that the small number of downstream moving particles in the denominator do not inflate the probability, and in such cases, the cells of $p_{et/ds}$ in Table 6.1 are marked with a dash line.

Fig. 6.1 shows the entrainment probability (p) as a function of L/D for both Series 1 and 3. The curves for the four particles are shown in four different colors, Series 1 as solid lines and Series 3 as dashed lines. Although the curves are plotted for the same cavity aspect ratio and under the same free-stream flow conditions, Fig. 6.1 clearly shows that Series 3 has higher p at lower L/D but with increase in L/D , p continues to decrease until it finally merges with the p values from Series 1. This mismatch of p even at the same L/D becomes clearer if we examine the cavity depth values for these corresponding L/D in more detail. The difference in p is maximum between $L/D = 10 - 13$ for which the corresponding D in Series 1 is 77 mm - 101 mm and in Series 3 is 50 mm. Hence, it can be inferred that the lower D in Series 3 is leading to higher entrainment probability in spite of the fact that the cavity aspect ratio (L/D) is equal in both Series 1 and 3. This is also supported by the p values beyond $L/D = 13$ where we see a similar p for SP2, SP4 and SP5 because now the corresponding D have come closer: 53 mm - 65 mm in Series 1 and 50 mm in Series 3. The SP6 particle with the lowest Shields parameter value among all the particles (please refer to Table 4.2 or Table 5.2 for particle properties) shows overall lower entrainment probability (p) and also higher

Figure 6.1 Entrainment probability (p) as a function of L/D

difference in p between Series 1 and 3. This demonstrates that particles with low Shields parameter (τ^*) are more readily affected by D than the other particles with relatively higher τ^* , which was also witnessed in Chapters 4 and 5 previously. This effect of cavity geometry on p may be better understood if we also examine the relationship between the downstream probability (p_{ds}) and the intermediate probability ($p_{et/ds}$) with the cavity aspect ratio (L/D), as is done in the following paragraphs.

Fig. 6.2 shows the downstream probability (p_{ds}) plotted against the cavity aspect ratio. This plot exhibits three important features concerning particle movement immediately after it is released at the cavity center. First, it shows that the particles could move both in the downstream and upstream directions in the cavity. The latter is reflected by the data-points where $p_{ds} < 1.0$ for a wide range of L/D from 8.9 - 15. However, with increase in L/D (or

Figure 6.2 Downstream probability (p_{ds}) as a function of L/D

decrease in D), the number of particles moving downstream are seen to increase and subsequently p_{ds} reaches 1.0 at $L/D \approx 15$ and beyond. Second, this plot has a relatively better overlapping irrespective of the particle type or particle Shields parameter (τ^*), indicating that p_{ds} is less affected by τ^* than is p as seen in Fig 6.1, especially for the SP6 curve. Third, here too, Series 3 (dashed lines) shows higher downstream movement probability compared to Series 1 for the same range of $L/D = 10 - 13$, as is also seen in Fig. 6.1. Thus, even for the same L/D , more particles are seen to move downstream in Series 3 ($D = 50$ mm) than in Series 1 ($D = 77$ mm - 101 mm). It must be noted that the movement of particles upstream or downstream from the cavity center is primarily affected by the presence of the clockwise rotating recirculation eddy in the cavity whose size and strength influences the downstream movement probability p_{ds} . Even for the same L/D , a lower D likely will result in a weaker recirculation vortex at the cavity center, and this weaker eddy is

unable to successfully pull the particles upstream, resulting in the higher downstream probability as shown in Fig. 6.2. This higher influence of D over L is similarly highlighted when $L/D > 13$. In this case when $L/D > 13$, Series 1 and 3 have similar D (53 mm, 65 mm in Series 1 and 50 mm in Series 3), which likely leads to similar characteristics of the recirculation vortex in terms of size and strength, as is inferred from Fig. 6.2, which shows similar values of p_{ds} . Recirculation vortices in shallow cavities with aspect ratio ≈ 10 have also been observed by Esteve et al. (2000), Reulet et al. (2002), Zidanski et al. (2008), and Madi Arous et al. (2011). Clearly, the present limited data cannot provide a comprehensive picture on how L and D , and perhaps even the approach flow depth affect the formation of the recirculation vortex and the resulting probability distribution; suffice to say that the observations are correct and accurate for the range of L and D used in this study (h being constant throughout at 0.12 m).

The intermediate probability ($p_{et/ds}$) is plotted with respect to the cavity aspect ratio in Fig. 6.3. An important feature in this plot is that the $p_{et/ds}$ curves do not overlap each other as they did in Fig. 6.2 for p_{ds} ; however, the curves for the same particle are seen to be clustered together. Furthermore, if the particles' Shields parameters are taken into consideration, the curves for the four different particles appear to be arranged as per each particle's Shields parameter values, although its effect on $p_{et/ds}$ is not linear due to a clear saturation of the effect as seen in Fig 5.1. The $p_{et/ds}$ values related to SP2 and SP4 particles (which have higher τ^*) in both Series 1 and 3 approach 1.0, showing that they are essentially totally entrained once they have moved downstream from the original at rest position. For SP6 with its lowest τ^* among all the particles, $p_{et/ds}$ is significantly higher in Series 3 than in Series 1 for $L/D = 11 - 17$ (or $D = 50$ mm in Series 3 and $D = 60$ mm - 90 mm in Series 1). However, the probability values collapse when both series have a similar D beyond $L/D = 17$. In summary, the figure shows that D is more influential in deciding $p_{et/ds}$ especially with decrease in τ^* . However, for Series 3, although all the particles, upon reaching the cavity downstream edge, only need to jump the same height of 50 mm for

all L/D , the $p_{et/ds}$ values still vary with L/D (as in SP5 and SP6) and are not perfectly horizontal curves as one may have surmised had they depended entirely on D . Thus, although D seems to be more influential here in affecting $p_{et/ds}$, L cannot be ignored as well.

Figure 6.3 Intermediate probability ($p_{et/ds}$) as a function of L/D

From Figs. 6.1 - 6.3 and the above discussion, it can be readily concluded that particle entrainment from a shallow rectangular cavity cannot be completely defined in terms of the cavity aspect ratio (L/D) alone. All the three figures highlight that even for the same L/D in Series 1 and 3, Series 3 with its lower cavity depth (D) has higher p , higher p_{ds} , and higher $p_{et/ds}$ when compared to Series 1. This is because even at constant L/D , a lower D results in a weaker recirculation eddy, thus limiting the eddy's ability to pull the particles upstream and hence increasing the downstream probability p_{ds} . When more particles have

reached the cavity downstream edge, it is again easier for them to be entrained from a cavity with a lower D , thus increasing $p_{et/ds}$. Thus, the entrainment probability p , which is a product of the other two probabilities, also increases. However, the figures also show that although D is more influential, L does not play an unimportant role, as is seen in the SP5 and SP6 curves in Fig. 6.3 and the discussion in the preceding paragraph.

All the 3 figures show that D needs to be given a higher weighting than L ; and use of the aspect ratio, L/D that gives equal weight to both L and D is not adequate. Furthermore, the better overlapping in Fig. 6.2 than Fig. 6.3 also indicates that between p_{ds} and $p_{et/ds}$, the latter rely more heavily on D than the former. Devising a parameter with unequal weights on L and D is not feasible if the parameter is to be kept dimensionless too. To address this issue, the aspect ratio L/D is multiplied with another dimensionless ratio D/H , which was also used in Chapter 4. This new parameter can then be expressed as $(L/D)(D/H)^a$ where the magnitude of the exponent a is expectedly higher for $p_{et/ds}$ than for p_{ds} , because of the higher dependence of the former on the cavity depth. This new exponent will thus ensure that for any given particle, the probability values for Series 1 as well as Series 3 match each other.

Using a trial-and-error approach, the exponent in $(L/D)(D/H)^{a1}$ for p_{ds} is obtained, with $a1 = -0.17$ giving the best collapse as seen in Fig. 6.4. The downstream probability seems not to be much influenced by the particle properties, as is also seen previously in Fig. 6.2, and hence a reasonable collapse is attained using only the cavity geometrical parameters L , D and H .

Similarly, the exponent in $(L/D)(D/H)^{a2}$ for $p_{et/ds}$ is obtained at $a2 = -0.6$, and the probability plot is shown in Fig. 6.5. This exponent is higher because jumping out of a cavity once the particle has already reached the cavity downstream edge is more dependent on D , when compared to the dependence of p_{ds} on the same cavity depth. Fig. 6.5 shows that for any given particle, the corresponding solid line and dashed line give an overall better

Figure 6.4 Downstream probability (p_{ds}) as a function of $\left(\frac{L}{D}\right)\left(\frac{D}{H}\right)^{-0.17}$

overlap now compared to that in Fig. 6.3. All the 8 curves do not overlap each other as is the case in Fig. 6.4 for p_{ds} because $p_{et/ds}$ is also influenced by the particle properties and the shear velocity which are not included in this parameter. Nevertheless, all the curves for the different particles more or less remain arranged in order of their Shields parameter values.

Higher improvement in overlap in Fig. 6.5 could not be achieved because of the following reasons. As mentioned earlier, when downstream moving particles were <10 , the corresponding datapoints were ignored. This was done because in such cases, the denominator in $p_{et/ds}$ was getting reduced, thus inflating the overall probability compared to p and p_{ds} , where the denominator was higher at 50. This led to plotting the $p_{et/ds}$ curves with fewer datapoints. Moreover, as the denominator in $p_{et/ds}$ was reduced to

Figure 6.5 Intermediate probability ($p_{et/ds}$) as a function of $\left(\frac{L}{D}\right)\left(\frac{D}{H}\right)^{-0.6}$

below 50 for most of the datapoints, there was slight increase in the error margins of the probability values for the overall plot. These two factors made it difficult to arrive at any better expression of the x-axis parameter using regression tools than that already presented here. Moreover, if all the curves in Fig. 6.5 are closely examined and compared to other probability curves, it can be understood that all the 8 curves correspond to different portions of an S-shaped curve. The curves for the particles SP2 and SP4 correspond to the extreme top portion of the S-curve where the probability value is maximum at 1. The curve for SP5 also corresponds to the top part of the S-curve but the part where probability value has not yet reached its maximum. Finally, the curve for SP6 corresponds to the sloping part of the S-shaped curve. Due to the curves being incomplete S-shaped curves, better regression results could not be obtained.

6.3 Cavity flow field for different cavity configurations: PIV results

In Section 5.3, the flow field in the free-stream region and 3 different planes inside the cavity (streamwise planes - PL01 and PL02, spanwise plane - PL03) were discussed. In this section, further discussion on the spanwise flow field along PL03 will not be provided as it was already examined in details in Section 5.3. Instead, the flow field at the cavity center (i.e. initial release position of the particles) which has not been discussed previously, will be considered here in a new streamwise plane PL04 along the cavity centerline $z = 245$ mm. The free-stream flow field shown in Section 5.3 and in this section are the same (flow configuration F1, please refer to Table 4.2 for more details); hence this section is primarily restricted to the study of 3 streamwise planes - PL01, PL02 and PL04. For a quick reference, an illustrative sketch of these 3 planes along with the coordinate system is provided in Fig. 6.6. For more details of the test set-up, please refer to the PIV experimental set-up diagram in Fig. 3.3. The flow field measurements along PL04 have been conducted in a way such that the cavity center is also the center of the PIV images.

Figure 6.6 Illustrative sketch of coordinate system showing all the 5 PIV measurement planes (not to scale)

Here, the PIV flow field results at 6 different cavity configurations will be explored - 3 from Series 1 (having 3 different L/D ratios where L is constant, D is varied), and another 3

from Series 3 ((having the same 3 L/D ratios as in Series 1 but here L is varied, and D is kept constant). These cavity configurations are a subset of the ones listed in Table 6.1, and for ease of reference, are provided in Table 6.2 below.

Table 6.2 Cavity geometrical parameters for which PIV flow field measurements are conducted

L/D	Series 1		Series 3	
	L (mm)	D (mm)	L (mm)	D (mm)
18.9	1000	53	945	50
13.0		77	650	
9.9		101	495	

All the PIV images capture the flow field for at least 0.2 m in the streamwise direction (x), and the maximum extent of coverage is limited to ~ 0.3 m. In the vertical direction (y), however, the entire water depth is covered - from the cavity bed to the free surface. These flow field figures in the present chapter are presented in a normalized form, with the x-axis normalized by the cavity length (L) and y-axis by the cavity depth (D). Thus, all the flow field figures for Series 1 (fixed L , varying D), have similar x-axis range when x/L is used, but varying y/D range, from -1 to H/D . The reverse is true for figures corresponding to Series 3 (varying L , fixed D) where for a given x , the range of x/L will be varying depending on the L , but the y/D range along the y-axis will be the same for all the cavity configurations. This gets clearer when one refers to the x , y axes in Fig. 6.7 sub-figures (a), (c), (e) for Series 1 where the x-axis range is similar across all the 3 sub-figures but the y/D range is different. The opposite is true for the Series 3 sub-figures – (b), (d) and (f).

6.3.1 Flow field characteristics at cavity center (PL04)

Fig. 6.7 shows the streamlines at the time-averaged flow at the cavity center (PL04) for different cavity configurations: (a) and (b) cavity aspect ratio $L/D = 18.9$ for Series 1 and 3,

Figure 6.7 Streamlines for the time-averaged flow at PL04: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

respectively; (c) and (d) $L/D = 13.0$ for Series 1 and 3, respectively; and (e) and (f) $L/D = 9.9$ for Series 1 and 3, respectively. The flow field sub-figures in the subsequent figures will also follow the same order as in Fig. 6.7. Here, $|V|$ denotes the flow velocity magnitude. In all the sub-figures, $x/L = 0.5$ corresponds to the cavity center, i.e. the initial release position of the particles, and $y/D = 0$ refers to the cavity top or the approach level. Figs. 6.7 (a) and (b), which have the same aspect ratio (L/D) = 18.9 and similar cavity depth (D) = 53 mm and 50 mm, respectively, have almost identical flow fields with uniformly straight horizontal streamlines. In the remaining sub-figures, as L/D decreases, a recirculation eddy is seen to form, whose size increases with decrease in L/D . However, when the sub-figure (c) is compared to (d), and (e) is compared to (f), the data show that the area of influence of the clockwise rotating recirculation vortex is larger when D is larger (even for the same L/D) and hence in such a case, particles are easily influenced and pulled upstream in the cavity, thus resulting in lower p_{ds} in (c) compared to (d) although they have the same L/D . This is also the case for the cavity configuration in (e) when compared to that in (f). The presence of this recirculation vortex, thus explains the differences in the downstream probability (p_{ds}) between Series 1 and Series 3 even for the same L/D as seen previously in Fig. 6.2. With few particles moving downstream for cavity configurations in (c) and (e), the final entrainment probability (p) is lower for Series 1 when compared to Series 3, as is shown in Fig. 6.1.

Fig. 6.7 highlights the presence of a recirculation vortex at the cavity center based on the time-averaged flow field. However, in spite of the presence of this eddy at $L/D = 13$ and 9.9, the downstream probability (p_{ds}) at these cavity configurations is non-zero as seen in Table 6.1 and Fig. 6.2. Thus there is a need to look into the instantaneous flow fields as well, and confirm if the recirculation vortex exists in the same size and form at every flow instant. Accordingly, the streamlines of the instantaneous flow field are plotted in Fig. 6.8. Fig. 6.8 (a) and (b) show only some wavy streamlines near the cavity bed which is consistent with its straight horizontal streamlines in Fig. 6.7 (a) and (b). In comparison, sub-plots (c) -

Figure 6.8 Streamlines for the instantaneous flow at PL04: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

(e) show a large amount of imperfectly-formed small scale vortices which upon time-averaging result in the well-defined recirculation eddy seen in Fig. 6.7 (c) - (e). These random small scale irregular eddies at the cavity center are the ones responsible for the stochastic nature of particle entrainment, sometimes drawing the particles towards the upstream end of the cavity and at other times, moving them downstream towards the cavity trailing edge. Even for the same L/D , there appears to be more of these small-scale vortices when D is higher as seen in the sub-figures (c) - (e).

In order to have a better understanding of the magnitude of the streamwise (V_x) and vertical velocity (V_y) across different flow regions, the velocity profiles at the free-stream region, and in the planes PL01, PL02 and PL04 for the cavity configuration: $L = 1000$ mm, $D = 53$ mm, $L/D = 18.9$ are plotted in Fig. 6.9. The velocity profile in the free-stream region is obtained after time-averaging the instantaneous velocities at 1 m upstream of the cavity leading edge, and is not space-averaged due to the already uniform nature of the flow in the free-stream region. However, because the non-uniformities in the flow regime inside the cavity, the velocity profiles for PL01, PL02 and PL04 are plotted after time-averaging as well as space-averaging the velocity data. For PL01 and PL02, the velocity is space averaged at intervals of $x = 1.5$ mm between 25 - 35 mm upstream from the cavity trailing edge, and for PL04, between $x = 5$ mm upstream to 5 mm downstream of the cavity center. Fig. 6.9 (a) shows that inside the cavity, the streamwise velocity, V_x is higher at the cavity center (PL04) than that near the downstream edges (PL01 and PL02). Fig. 6.9 (b) shows that while the vertical velocity, V_y in PL01 and PL02 is positive, thus aiding the particle to jump over the cavity edge, V_y at the cavity center is negative throughout the entire flow depth. This is also consistent with observations made during the experiments - that lift offs were witnessed only near the cavity downstream edge and never at the cavity center, i.e. all particles, upon their release, rolled along the cavity bed to reach either the upstream or downstream edges, and were never observed to lift off during this movement. Only upon reaching the cavity

trailing edge, did they experience a positive V_y , enabling their entrainment from the cavity. Overall, the flow velocities inside the cavity seem to follow the trend below:

Figure 6.9 Time averaged and space-averaged velocity profiles in different planes (a) streamwise velocity, V_x ; (b) vertical velocity, V_y

V_x (PL04: cavity center) $>$ V_x (PL01: downstream central cavity plane) $>$ V_x (PL02: downstream corner cavity plane)

V_y (PL02: downstream corner cavity plane) $>$ V_y (PL01: downstream central cavity plane) $>$ V_y (PL04: cavity center).

Since the streamwise velocity (V_x) is the most important parameter in deciding if a particle is likely to go upstream or downstream in the cavity, it is imperative to further scrutinize V_x for all the cavity configurations. Fig. 6.9 (a) only presented the V_x profile for one cavity configuration at one particular location in the cavity. To supplement this, contour plots of the time-averaged V_x at different cavity configurations are presented in Fig. 6.10. The sub-figures clearly establish that for $L/D = 13$ and 9.9 , V_x at the cavity center is lower (or more negative), when D is higher even for a constant L/D . Thus, it is not surprising that all the downstream probability (p_{ds}) curves did not collapse when plotted against L/D in Fig. 6.2.

Figure 6.10 Contours of time-averaged V_x at PL04: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

To further examine the streamwise velocity at the cavity center, the instantaneous V_x values at $x/L = 0.5$, $y = 5$ mm above the cavity bed are extracted from the flow field and their histograms plotted in Fig. 6.11 for all the 6 cavity configurations, using 6162 velocity data points for each cavity configuration. The increase in negative V_x with decreasing L/D can be quickly ascertained from the histograms from (a), (c), (e) for Series 1, and from (b), (d), (f) for Series 3. Additionally, normal Probability Density Functions (PDFs) of V_x are superimposed over the histograms which seem to give a good fit (R-squared = 0.938, 0.943, 0.95, 0.99, 0.96, and 0.97 for the sub-plots (a) – (f), respectively). Whereas instantaneous streamwise velocity follows a lognormal distribution over an open channel bed (Wu and Lin, 2002; Wu and Chou, 2003); in the present case, V_x at the cavity center follows a normal distribution with distribution parameters varying with changes in the cavity geometrical parameters.

In order to give a better perception on the probability of $V_x < 0$ for all these cavity configurations, the Cumulative Distribution Functions (CDFs) are plotted in Fig. 6.12. Fig. 6.12 (a) reveals that for a constant $L/D = 18.9$, when two datasets have similar D values (i.e. 53 mm in Series 1 and 50 mm in Series 3), the CDFs overlap each other with $P(V_x \leq 0) = 0.045$ for both Series 1 and 3. However, in sub-figure (b), although both the CDFs are for the same cavity aspect ratio = 13, $P(V_x \leq 0)$ is higher at 0.7 in Series 1 ($D = 77$ mm) compared to that in Series 3 at 0.5 ($D = 50$ mm). This is followed again in sub-figure (c) where for Series 1 ($D = 101$ mm), $P(V_x \leq 0) = 0.95$ and for Series 3 ($D = 50$ mm) it is 0.81, although L/D is constant at 9.9. Thus, the V_x CDF curves from these PIV results reinforce the different downstream probability curves seen in Fig. 6.2 for the same L/D .

Figure 6.11 Histograms and normal PDFs of instantaneous V_x near the cavity center for different cavity configurations: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

Figure 6.12 CDFs of instantaneous V_x near the cavity center for different cavity configurations: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

Hitherto, only the flow field velocity data were shown from Fig. 6.7 to 6.12. For a better understanding of these flow fields, the corresponding TKE plots are presented in Fig. 6.13. It can be seen from the figure that with decrease in L/D , the TKE increases and the region with the highest TKE values (seen as the red zone and surrounding area in all the sub-figures) rapidly expands for Series 1. However, this zone is seen to reach the cavity center earlier in Series 3 compared to Series 1, owing to the low cavity depth (D) in the former, and thus, contributing to the higher downstream probability (p_{ds}) in Series 3 even for the same L/D ratio.

From Figs. 6.7 - 6.13 it may fairly be concluded that for any cavity configuration, even at the same L/D , the cavity depth (D) carries a higher importance when it comes to affecting particle downstream probability, and eventually the entrainment probability. At the same L/D , a lower D leads to (1) a smaller, weaker clockwise recirculation vortex (Fig. 6.7 - 6.8), (2) a lower streamwise velocity (Fig. 6.10 - 6.12) at the cavity center, and (3) a higher TKE at the same cavity center (Fig. 6.13). All these factors translate into a higher p_{ds} as exhibited in Fig. 6.2.

Figure 6.13 Contours of TKE at PL04: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

6.3.2 Flow field characteristics near cavity downstream edge (PL01 and PL02)

After a particle has moved away from the cavity center or the recirculation bubble's influence region towards the cavity downstream edge, it now faces the uphill task of being entrained from the cavity. This entrainment has been observed to take place only from a position close enough to the cavity edge $\sim 0 - 60$ mm from the downstream edge. Hence, the flow field near the cavity trailing edge decides the intermediate probability ($p_{et/ds}$) and therefore, the final entrainment probability (p). For a cavity configuration where there is no downstream movement of the particle, the flow field characteristics near the cavity edge are irrelevant. However, depending on the particle properties, there can be non-zero downstream probability (p_{ds}) even at very low L/D ratios as witnessed for the SP2 particle at $L/D = 9.9$ where $p_{ds} = 0.02$, despite all other 3 particles showing $p_{ds} = 0$. Hence, for a comprehensive understanding, this section will look into the flow fields near the cavity edge for all the cavity configurations discussed in Figs. 6.7 - 6.13. Specifically, the flow fields will be examined for the planes - PL01 (along the streamwise cavity centerline) and PL02 (parallel to the cavity side wall at $z = 1$ cm).

Fig. 6.14 shows the streamlines of the time-averaged flow along PL01 at the 6 different cavity configurations. This figure can be viewed in conjunction with Fig. 6.7 to have a comprehensive view of the flow field along the cavity centerline. In Fig. 6.14, for Series 1, as L/D decreases, the clockwise recirculation vortex at the downstream edge continues to grow; such that entrainment at $L/D = 9.9$ (Fig. 6.14 e) from this plane seems highly improbable. For Series 3, the increase in the size of the same eddy is less appreciable and entrainment looks equally likely for $L/D = 18.9$ and 13, but less promising for $L/D = 9.9$. However, when the Series 1 flow fields are compared with that of Series 3 for the same L/D , such as sub-figure (a) with (b), (c) with (d), (e) with (f), entrainment from Series 3 definitely appears to be more probable. This is owing to the low cavity depth (D) which results in a lower obstacle height as well as a smaller and weaker recirculation vortex.

Figure 6.14 Streamlines for the time-averaged flow at PL01: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

The streamlines of the instantaneous flow field at these cavity planes comprises many small scale random eddies, similar to those ones seen in Fig. 6.8 for PL04. Hence, the corresponding instantaneous flow fields are not shown for these planes here.

At the cavity downstream edge, V_y is likely to be more influential to effect a successful entrainment when compared to V_x . Taking this into account, the time-averaged V_y contour plots are presented in Fig. 6.15. In accordance with the streamlines seen in Fig. 6.14, a negative V_y is observed along the cavity edge at the location of the recirculation eddy seen in Fig. 6.14. Fig. 6.15 shows that with decrease in L/D , V_y in the region near the cavity downstream edge changes differently in Series 1 and Series 3. In Series 1, as L/D decreases, the negative V_y region inside the cavity and just near the edge, keeps increasing. Hence with decreasing L/D , the particle needs an increasingly higher upward force at the cavity bed to navigate this region successfully, thus leading to a lower entrainment. In contrast, in Series 3, the size of the negative V_y region is constant but the area of the positive V_y region at the interface of the cavity edge and flume bed keeps shrinking even at constant D , thus exerting a reduced influence on the particle lying on the cavity bed, and also reducing entrainment probability with decreasing L/D .

The TKE plots for PL01 are shown in Fig. 6.16. The sub-figures highlight the same characteristics as is also seen in PL04 (Fig. 6.13), that with decreasing L/D , the TKE increases. For the same L/D , although Series 1 shows a larger region with higher TKE values, the TKE at the cavity bed is higher in Series 3. This characteristic is seen to be more pronounced when sub-figures (e) and (f) are compared. Thus, the entrainment probability will be higher in the case of Series 3 which has lower TKE over the entire plane, but higher TKE at the cavity bed, the region from where all the particle lift-offs commence.

Figure 6.15 Contours of time-averaged V_y at PL01: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

Figure 6.16 Contours of TKE at PL01: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

During the course of conducting the experiments, more particles were witnessed to entrain from the cavity corners than from the cavity centerline. In order to investigate this, the flow field features near the downstream cavity corner, i.e. PL02, are discussed next.

Fig. 6.17 shows the streamlines for the time-averaged flow field in PL02. The most important characteristic distinguishing PL02 from PL01 is the absence of any large prominent recirculation vortex in the former which could have trapped the particle in it, and this likely translates into a higher entrainment probability from PL02. Another equally significant distinguishing factor can be observed near the cavity bed region, marked with a red circle, where the upstream moving flow from the cavity downstream edge and downstream moving flow from the upstream region are seen to "collide". The collision of the two flows may intermittently generate an instantaneous upward force of strong enough magnitude which initiates the particle lift-off and subsequently, results in the entrainment of the particle from the cavity. Also, the fact that particles spent more time away from the cavity centerline symmetry plane and near the sidewalls, may jointly be responsible for the higher entrainment from PL02 than from PL01. Comparing the flow fields, it is evident that the particles in Series 3 where the cavity depth D is lower compared to that in Series 1, also needs to adopt a shorter path to reach the cavity top as entrainments take place along the streamlines, which are short straight diagonal lines from the cavity bed to the cavity top in Series 3 but longer convex shaped lines in Series 1 (Figs. 6.17 c, e).

Fig. 6.18 shows the V_y contour plots for Series 1 and 3 for PL02. Whereas in Fig. 6.15 for PL01, V_y at the interface of the cavity edge and the flume bed, reduces with decreasing cavity aspect ratio in both Series 1 and 3, the trend in PL02 Series 1 is opposite to that in PL01. However, this is not the case for PL02 Series 3. In PL02 Series 1, the effect of increasing cavity depth (D) is slightly offset by a simultaneous increase in V_y at the cavity - flume interface (red contours). However, V_y at the cavity bed (blue contours) which is more influential in causing entrainment remains unchanged. In fact, the zone of high V_y in Series 1 reaches the cavity bed for sub-figure (a) only. In contrast, although the high V_y region keeps shrinking in Series 3 with

Figure 6.17 Streamlines for the time-averaged flow at PL02: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

Figure 6.18 Contours of time-averaged V_y at PL02: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

decreasing L/D , this zone still reaches the cavity bed, thus, generating a higher entrainment probability. Higher V_y in PL02 compared to that in PL01, consistently with a time-averaged flux from the symmetry plane to the side, contributes to the preferential uplift in PL02 rather than PL01.

The TKE plots for the cavity configurations are presented in Fig. 6.19. Compared to PL01 in Fig. 6.16, the TKE in PL02 is lower in all the sub-figures. Lower TKE in PL02 implies lower turbulence or lower randomness in the flow. However, more entrainments from this plane (PL02) compared to PL01 (which has higher TKE) imply that the higher entrainment in PL02 is likely due to the absence of a well-defined recirculation vortex in PL02, and higher V_y in PL02 compared to that in PL01. The TKE contours seem to follow the same trend as in the V_y contours in Fig. 6.18 which highlights that fluctuations in V_y rather than in V_x is the major contributor to the TKE for this plane.

From Figs. 6.14 - 6.19, it can be concluded that the intermediate probability ($p_{et/ds}$) is higher in Series 3 especially for the SP6 particle and to an extent for SP4 because of multiple factors. In Series 3 PL01, a smaller recirculation vortex, low cavity depth, smaller negative V_y region, and higher TKE at the cavity bed all lead to a higher $p_{et/ds}$ compared to Series 1 for the same L/D . Similarly, in PL02, the factors responsible for the higher entrainment in Series 3 are the absence of any recirculation vortex, the coming together of the upstream and downstream moving flow near the edge likely to cause easier particle lift-off, the absence or limited size of a negative V_y region, and higher TKE near the cavity bed, all accompanied with a lower cavity depth to cover in order to reach the cavity top and be entrained out successfully.

To summarize, Figs. 6.2 and 6.3 demonstrates that particle entrainment from the rectangular cavity with different configurations despite having the same aspect ratio (L/D) can exhibit different particle entrainment probabilities - be it the downstream probability

Figure 6.19 Contours of TKE at PL02: $L/D = 18.9$ [(a) Series 1, (b) Series 3]; $L/D = 13$ [(c) Series 1, (d) Series 3]; $L/D = 9.9$ [(e) Series 1, (f) Series 3]

(p_{ds}) or the intermediate probability $(p_{et/ds})$. This difference in the probability values are attributed to the dominance of D over L when considering entrainment from an open shallow rectangular cavity. As a result, p_{ds} and $p_{et/ds}$ are re-plotted in Figs. 6.4 and 6.5 substituting L/D with $(L/D)(D/H)^a \Rightarrow (LD^{a-1}H^{-a})$ where $a = -0.17$ and -0.6 for p_{ds} and $p_{et/ds}$, respectively, which brings the experimental data closer, considering the error margins associated with the probability values.

The dominance of D over L in affecting particle entrainment is corroborated by the flow field PIV results shown in Figs. 6.7 - 6.19. The common thread through all the flow fields is that lower D leads to different flow characteristics (even when compared to a cavity configuration with the same aspect ratio) that is more conducive for particle entrainment. The factors responsible for the higher particle entrainments from a cavity with a lower D for a constant L/D are many, as are already discussed in details. In summary, the primary reasons are, lower D results in a smaller and weaker clockwise-rotating vortex at the cavity center, and causes the formation of a higher TKE region near the cavity center, thus increasing p_{ds} (refer Figs. 6.7 and 6.13). Furthermore, $p_{et/ds}$ is higher at these cavity configurations due to the lower cavity depth the particle has to travel before it is entrained, an entrainment enabling V_y region and the effect of higher TKE at the cavity - flume bed interface influencing particles on the cavity bed easily due to the lower D .

6.4 Cavity flow field at different cavity depths (D): PIV results

In Chapter 4, particle entrainment from a rectangular cavity with different configurations (Series 1: constant L , varying D) was discussed. The entrainment probability curves, entrainment time distributions and plan-view particle trajectories were presented in the chapter, but not the PIV flow field results. To address these, this chapter presented some of the cavity flow fields pertaining to the Series 1 dataset in Section 6.3, specifically for 3 cavity

configurations: $L = 1000$ mm (constant), and $D = 53$ mm, 77 mm and 101 mm (see Table 6.2). However, in addition to these 3 cavity configurations in Series 1, PIV measurements are also conducted at 3 more cavity configurations with $D = 17$ mm, 29 mm and 41 mm (L being constant at 1000 mm). Hence, to give a more complete picture, the PIV results will be presented for all these 6 cavity configurations of Series 1 in the following section. This will be followed by a discussion of the large scale (LS) eddies at different cavity depths, and the TKE contributions of these LS eddies to the total TKE of the flow

6.4.1 Flow field characteristics at the cavity downstream edge (PL02)

In previous sections, the flow field results at 3 different planes - PL01, PL02 and PL04 were discussed for Series 1 as well as Series 3. However, this section will be restricted to only one plane PL02 since more particle lift-offs are seen to occur along this plane. However, flow field features in other planes PL01 and PL04 for Series 1 also follow the same trend as seen in the previous sections.

Fig. 6.20 shows the streamlines for the time-averaged flow field at PL02. For sub-figure (a) where D is the lowest at 17 mm, presence of the cavity is not significantly changing the cavity flow field as also evident from the plan-view straight line particle trajectories in Stage 01 (Fig. 4.9). In sub-figure (b), the upstream moving flow is seen to appear in a small region adjacent to the cavity downstream wall, and this region of upward moving flow keeps on growing in size with increasing cavity depth, as is shown in sub-figures (c) - (f). Hence, it may be inferred that for entrainment in a cavity with higher depth, the particle has to travel for a distance higher than the cavity depth, considering that particle entrainment is along the diagonal streamlines from the cavity bed to the cavity top; and this further leads to a corresponding decrease in the entrainment probability (p).

Figure 6.20 Streamlines for the time-averaged flow at PL02: (a) $D=17$ mm; (b) $D=29$ mm; (c) $D=41$ mm; (d) $D=53$ mm; (e) $D=77$ mm; (f) $D=101$ mm

However, this increase in D is also accompanied by an increase in V_y near the cavity - flume interface as shown in Fig. 6.21 (also shown in Fig.6.18). Unfortunately, there is no similar increase in V_y near the cavity bed where the particle is present. Therefore, this increase in V_y at the cavity top does not result in a higher particle entrainment. This ultimately leads to a lower p with increasing cavity depth. This decrease in p is also due to the fact that with an increase in D , a clockwise rotating vortex that forms at the cavity center, pulls the particle towards the cavity upstream region with no chances of any entrainment, and hence results in reduced entrainment. This recirculation eddy was previously discussed in more details in section 6.3.1.

Figure 6.21 Contours of time-averaged V_y at PL02: (a) $D = 17$ mm; (b) $D = 29$ mm; (c) $D = 41$ mm; (d) $D = 53$ mm; (e) $D = 77$ mm; (f) $D = 101$ mm

6.4.2 Large scale flow structures at the cavity downstream edge (PL02)

From the cavity flow fields presented in Figs. 6.20 and 6.21, it would appear that with a decrease in cavity depth (D), the flow field becomes more conducive for particle to be entrained, and thus there will be a gradual increase in entrainment probability (p) as a consequence of the corresponding decrease in D . However, this is not always the case as is seen earlier in Section 4.3.1 and also in Fig. 6.22 below, where the SP5 and SP6 particles have lower p close to the range $25 \text{ mm} < D < 53 \text{ mm}$, but higher p both below and above this range. Fig. 6.22 shows the entrainment probability curves for these two particles at different cavity depths and different flow configurations. SP6 is tested under three different flow configurations F1, F2, F3 (refer Table 6.3) and SP5 under F1; and the particle Shields parameter in these four cases are 0.0156, 0.0194, 0.0245 and 0.0253, respectively. The dip in the entrainment probability is attributed to the lower energy content of the large-scale (LS) eddies at these low cavity depths and this section will explore the characteristics of these LS eddies, especially their size and TKE content as a function of the cavity depth (D) and free-stream flow velocity (u).

To extract the dominant LS flow structures in the cavity flow, the Proper Orthogonal Decomposition (POD) method is used. POD decomposes a set of vector fields into an equal number of empirical eigenmodes, with each mode having an associated energy value, that can be used to examine the key dominant features in the flow contributing most to the TKE. Some of the studies using POD to describe the flow field are Adrian et al. (2000) for a turbulent pipe flow, Rossinova et al. (2010) on a smooth bed open-channel flow, Andrianne et al. (2011) for flow around a cylinder in a wind tunnel, Fernando et al. (2013) in a confined rectangular cavity flow, and many others. To the author's knowledge, POD in a shallow open rectangular cavity in open channel flows has not hitherto been studied.

Figure 6.22 Entrainment probability (p) as a function of cavity depth (D) for the particles SP5 and SP6 under different flow configurations

Table 6.3 Free-stream flow configurations F1 - F3 for Series 1 test runs

Flow Run	u (m/s)	u_* (m/s)	h (m)	Re_h	Fr_h	Q (m ³ /hr)
F1	0.260	0.0139	0.12	39000	0.240	55.0
F2	0.285	0.0155	0.12	42750	0.263	60.3
F3	0.322	0.0174	0.12	48300	0.297	68.2

The POD algorithm used here is the 'method-of-snapshots' implemented in the software Davis 8.3.0 from Lavision GmbH, the details of which can be found in Sirovich L (1987). For any cavity depth (D), a total of 6162 instantaneous flow fields are used, so as to capture all the dominant modes present in the cavity flow. This gives an equal number of eigenmodes (i.e. 6162) with mode 1 contributing the highest to the TKE of the flow field, and the contribution of subsequent modes decreasing in an exponential fashion. Fig. 6.23 illustrates the TKE contributions of all the modes for the 6 cavity configurations of Series 1, plotted on a log-log scale. It can be easily seen that the contributions from each mode decreases very fast in all the cavity depths, with the contribution beyond Mode 10 essentially become insignificant, with 1% TKE contribution for Mode 10 and 0.0001% for Mode 6162.

Figure 6.23 Percentage (%) TKE contributions of all the modes in PL02 for the 6 cavity configurations in Series 1

Table 6.4 lists the individual % TKE contributions of modes 1-6 for the 6 cavity configurations and Figs. 6.24 - 6.26 shows these 6 modes for $D = 17$ mm, 29 mm and 53 mm, respectively. The table clearly shows that as the cavity depth increases, the energy contribution of the dominant modes increases, with mode 1 contributing a mere 3.96% at $D = 17$ mm but a five-fold increase to 21% at the maximum cavity depth of 101 mm.

Table 6.4 Percentage (%) contributions to TKE from the first 6 modes at different cavity depths (D)

D (mm) \ Mode #	17	29	41	53	77	101
1	3.96	4.13	6.33	8.98	18.30	21.02
2	3.51	3.82	4.25	5.63	5.25	8.80
3	2.22	2.68	3.45	4.10	4.59	5.31
4	1.84	2.19	2.51	3.08	3.43	4.82
5	1.49	1.98	2.13	2.74	2.27	4.11
6	1.45	1.68	1.68	2.01	2.05	2.80

In each of Figs. 6.24 - 6.26 from sub-plots (a) - (f), it can be observed that the first few modes with the highest TKE contributions all are large scale eddies covering the entire flow depth (H), with lower modes comprising more number of eddies but with reduced size. Furthermore, it can also be seen that the reduction in size of these LS eddies is most conspicuous for the flow field at the shallowest cavity, $D = 17$ mm, and least at $D = 53$ mm. For $D = 17$ mm (refer Fig. 6.24), mode 1 contains LS eddies whose area covers almost one-third of the flow field area captured by PIV, whereas each eddy in mode 6 covers only approximately one-ninth of the same flow field area. Again, for $D = 53$ mm (refer Fig. 6.25), the LS eddy in mode 1 and 2 is even larger than the flow field area captured by the

Figure 6.24 Large-scale flow structures obtained from POD for $D = 17$ mm; (a) – (f) shows modes 1- 6 respectively

Figure 6.25 Large-scale flow structures obtained from POD for $D = 29$ mm; (a) – (f) shows modes 1- 6 respectively

Figure 6.26 Large-scale flow structures obtained from POD for $D = 53$ mm; (a) – (f) shows modes 1- 6 respectively

PIV system, and hence is not fully reproduced in the image, whereas the eddies in mode 6 are smaller and cover only one-third of the same area. This change in the size of the LS eddies with changing cavity depth, plays a significant role in particle entrainment as well.

The total TKE contributions of these first 6 modes at different D is shown in Fig. 6.27 for different flow configurations (see Table 6.3). The data show that when D increases, so does the total TKE contribution of these modes. In other words, the first 6 modes at lower D contribute less to the overall flow field's TKE than the modes at higher cavity depth. This is in addition to the fact that the TKE is already less at lower D , as seen in Fig. 6.19. Thus, in an absolute sense, dominant modes at shallower D have lower TKE when compared to those at higher D . This is due to the limiting effect of the flow depth (H) as well as the generating effect of cavity depth (D) that limits the size of the LS eddy in the vertical direction. Generally, one would surmise that particle entrainment probabilities at shallower cavities would be definitely higher than at deeper cavities, but this observation of LS eddies having lower TKE when D is lower sheds a different light on the entrainment phenomenon and can help explain the deviations seen in Fig. 6.22 for the range $D \approx 25 \text{ mm} - 53 \text{ mm}$. For this range of cavity depth, although D is lower, so is the TKE of the dominant modes, resulting in a lower entrainment probability (p), signifying that it is more difficult for the particle to be entrained. Consequently, the particles with lower Shields parameter (τ^*) - SP5 and SP6 are unable to follow the same inversed S-curve trend as the other particles. However, for extremely shallow cavities such as the one where $D < 25 \text{ mm}$, there is hardly any effect on the streamlines as seen in Fig. 6.20 (a) and entrainment is higher (Fig. 6.22). At D higher than this range, the dominant modes have higher TKE, and if sufficient lift from either small scale random fluctuations or from these LS eddies is applied on a particle, entrainment will take place.

Figure 6.27 Percentage (%) TKE contribution of first 6 modes in PL02 as a function of cavity depth (Series 1) for flow configurations F1 - F3

For the same cavity configuration, as the free-stream flow velocity is increased, the TKE in the flow correspondingly increases as is shown in Fig. 6.28 for flow configurations - F1, F2 and F3. However, the trend shown in Fig. 6.27 still holds as is confirmed by the 3 data-points for F2 and F3. Because of the higher absolute TKE content in the flow in F2 and F3 along with higher mean velocity and stress, the particle SP6, which earlier had a lower probability of entrainment with F1, can now attain a higher p -value, as is seen in Fig. 6.22 for the SP6 curves at F2 and F3. Thus, when all the turbulence in a flow field, be it in the form of small-scale random fluctuations or large-scale eddies, along with the streamlines of the time-averaged bulk flow are considered in an integrated manner, all the entrainment probability curves seem to make proper sense.

Figure 6.28 Contours of TKE at PL02 for $D = 53$ mm: (a), (b), (c) are for flow configurations F1, F2 and F3 respectively

6.5 Summary

The present chapter explores the effect of different cavity configurations on particle entrainment. Two sets of experimental data - Series 1 with varying D , constant L , and Series 3 with varying L , constant D are compared. The entrainment probability (p) is sub-divided into a downstream probability (p_{ds}) and an intermediate probability ($p_{et/ds}$), and are examined as a function of the cavity aspect ratio (L/D). For the same L/D in both the datasets, Series 3 with lower D than Series 1 constantly showed higher p , higher p_{ds} and higher $p_{et/ds}$. This is because lower D results in a weaker recirculation vortex, thus increasing p_{ds} . Moreover, once the particles have reached the cavity downstream edge, a lower D leads to easier entrainment - increasing $p_{et/ds}$; and this increase in p_{ds} and $p_{et/ds}$ due to lower D ultimately leads to higher p . Hence, instead of giving equal weight to both L and D for describing entrainment probability data, D is made over-weight by using a dimensionless product of L/D and D/H with different exponents for the second term, which results in a better overlap of the experimental data. It must be noted that experimental results are obtained from a limited dataset where only two sets of different L and D are used (Series 1 and 3); however, the results give us enough insight into the particle entrainment process and the corresponding cavity flow fields, at least for the range of L and D used in the experiments.

The entrainment data were further corroborated by the PIV flow field results for different cavity configurations. For the cavity configurations used in the study, PIV measurements at the cavity center confirm the existence of a clockwise recirculation vortex whose size continues to increase with a decrease in the cavity aspect ratio, and subsequently reduces particle entrainment. The instantaneous streamwise velocity (V_x) at the cavity center is observed to follow a normal distribution which is in contrast to the velocity in open channel flows that follow a lognormal distribution, as is advocated by Wu and Lin (2002), and Wu and Chou (2003). For the two datasets with the same L/D , the CDFs of instantaneous V_x at

the cavity center show higher probability of negative V_x for the dataset with higher D . Similarly, for the same L/D , the cavity center also exhibits a higher TKE for the dataset when D is lower.

Between the two planes near the cavity downstream edge PL01 (downstream central cavity plane) and PL02 (downstream sidewall cavity plane), the flow field along PL02 is observed to be more conducive to particle entrainment. This is primarily due to the absence of a well-defined recirculation vortex near the cavity downstream edge in PL02 which is otherwise prominent and well-pronounced in PL01, thus reducing particle entrainment. For the same L/D , the cavity configuration with a lower D also has the same vortex but with a reduced size. All these factors lead to higher entrainment from PL02 than PL01, despite the fact that PL01 has substantially higher TKE than PL02.

Section 6.4 discusses the effect of varying D (constant L) on entrainment probability. Apart from discussing the streamlines and V_y contour plots in PL02, the section also dwells upon the large scale (LS) eddies in the cavity flow found at different cavity setups. These LS eddies are extracted from the flow using the POD method. The results show that at lower D , dominant modes consisting of LS eddies have overall lower TKE than the dominant modes at higher cavity depth, due to the size of the LS eddy in the vertical direction being limited by H . Thus, although D is lower and consequently less work is needed to lift the particle to the cavity top, the energy supplied by the flow to the particle is lower too, and this is likely the cause behind the deviations seen in the SP5 and SP6 curves in Fig. 6.22.

To conclude, even for the same L/D , the cavity configurations with a lower D is observed to cause higher entrainment for a multitude of factors, and consequently higher weight needs to be given to D as compared to L . The entrainment probability data is substantiated by the PIV flow field results both at the cavity center and near the downstream edge. Additionally, LS eddies at lower D are seen to have correspondingly lower TKE content due to the limited flow depth available, leading to reduced entrainments, especially for particles with a relatively lower Shields parameter.

Chapter 7

Conclusions and recommendations

7.1 Conclusions

This study focuses on investigating the probabilistic entrainment of particles from a rectangular cavity in a turbulent open channel flow. Three series of experiments are conducted to study this entrainment phenomenon under different test parameters - cavity depth (D), free-stream velocity (u) and cavity length (L) (or cavity aspect ratio (L/D)). Complimentary flow field measurements at different test conditions using Particle Image Velocimetry (PIV) are also conducted. The following sections highlight the key results and conclusions that can be drawn from these three experiment series.

7.1.1 Effect of cavity depth on particle entrainment

A conceptual model and various flow field scenarios presented in Chapter 4 shows that particle movement and entrainment from a rectangular cavity is highly stochastic in nature. This is corroborated by the particle entrainment probability (p) plots (refer to Fig. 4.7) and entrainment timescales (t) (refer to Fig. 4.8), in which particles are entrained from the cavity with varying success rate and varying time intervals depending on the cavity depth (D). The entrainment probabilities when plotted with respect to D/H essentially follow a reverse S-shaped curve, and the entrainment durations generally can be fitted to a lognormal probability density function. No critical or threshold value of D/H , is found which could strictly demarcate the $p = 0$ region from the $p = 1$ region. This is in contrast to past studies by Shields (1936) and Sumer et al. (2001) where a critical value of τ^* was presented for separating entrainment and no-entrainment in case of the flat sediment beds and gaps between armor blocks, respectively. In this test series, the variation in entrainment probability from $p = 0$ - 1 takes place due to changes in the cavity flow field as a result of

changing D , and the free-stream flow configuration is kept constant throughout the experiments. Furthermore, particles are observed to be entrained at time intervals ranging from $t = 10 - 120$ sec or to a maximum of 600 sec for any particular test run without even changing any test parameter. This behavior confirms the randomness in the cavity flow field leading to entrainments occurring in a few seconds to a few minutes and in some instances no entrainment at all. This stochastic effect of D on the entrainment behavior is again exemplified when the plan-view particle trajectories are presented in Fig. 4.9. The trajectories show that with an increase in D , the cavity flow field transitions from a unidirectional flow (streamwise only), to a flow with significant secondary currents and flow reversals. This leads to particles in the cavity moving not just in the spanwise direction, but also in a direction opposite to the free-stream flow direction.

The deviations of the entrainment probability curves (Fig. 4.7) for particle SP6 is attributed to the complex relationship between the particle properties and the dependence of cavity flow field characteristics on D , especially the presence of large scale eddies. This is further validated in Chapter 6 using the Proper Orthogonal Decomposition (POD) analysis of the vector fields obtained using PIV measurements.

7.1.2 Particle entrainment under varying free-stream flow velocity

In Chapter 5, the particle entrainment probability (p) is calculated under different free-stream velocities (u) but constant cavity configuration. The particle Shields parameter (τ^*) is computed using the free-stream shear velocity (u_*) instead of the local shear velocity inside the cavity, because of the steady, unidirectional and uniform nature of the flow in the free-stream region which stands in stark contrast to the multi-directional and non-uniform flow prevailing inside the cavity. The steady uniform flow profile in the free-stream region allows a proper log-law fit and the subsequent u_* computations. The τ^* of the particles are compared to the critical values proposed by Shields (1936) and Sumer et al. (2001) in Fig. 5.1, and the results show that entrainment from a cavity can occur at τ^* values significantly lower than that proposed in those two studies. This is despite the fact that the streamwise velocity near the cavity downstream edge is comparatively lower than that in the free-stream

region (refer Fig. 5.3 and 5.4). However, this decrease in streamwise velocity near the cavity downstream edge is also accompanied by an increase in the vertical velocity, increase in TKE as well as the presence of many irregularly formed small-scale vortices close to the cavity bed. Thus the difficult task of entraining a particle upwards over a distance several times the particle diameter is made somewhat easier in an instantaneous sense due to the flow unsteadiness near the cavity edge.

The side-view trajectories in Fig. 5.9 and Fig. 5.12 that show the particle motion from the cavity bed to the cavity top provide further insight into the entrainment process. Experimental observations show that the particle (especially in Fig. 5.9 (a)) does not simply move in a straight upward path during entrainment but undergoes considerable up-down and to-and-fro movements during the process. This shows that even after a particle has received a strong enough upward force at the cavity bed to be lifted initially, its subsequent entrainment is still dependent on the cavity flow field which is changing from one instant to another (see Fig. 5.12). The deeper the cavity and therefore, the longer the vertical distance the particle has to cover, the longer is the duration over which the turbulent cavity flow can influence the particle path and its entrainment.

7.1.3 Effect of cavity geometry on particle entrainment and cavity flow field

Past studies on rectangular cavity flows have mostly used the cavity aspect ratio (L/D) to define the flow characteristics inside the cavity. However, in the case of particle entrainment from such a cavity, the experimental results in Chapter 6 demonstrate that instead of L and D having equal influence on entrainment, D plays a more crucial role in determining the entrainment probability. Hence, L/D is used in conjunction with $(D/H)^x$ where the exponent x has different values for the downstream probability (p_{ds}) and intermediate probability ($p_{et/ds}$). However, it must be mentioned that these results are obtained using a limited dataset (Series 1 and 3), and further tests with a wider range of L and D may bring to light other insightful features about this entrainment phenomenon.

PIV measurements of the flow field show that even with a constant L/D , a lower D leads to a weaker recirculation vortex, thus enabling particles to move downstream comparatively easily (refer Figs. 6.7 and 6.8). Moreover, for the same L/D , once the particle has reached the cavity downstream edge, it is easier for it to be entrained when D is less than when D is higher. The instantaneous streamwise velocity (V_x) at the cavity center shows a normal distribution (refer Fig 6.11) which is in contrast to the streamwise velocity on flat beds in open channel flows that follow a lognormal distribution as shown in Wu and Lin (2002) and Wu and Chou (2003). Even for the same L/D , Fig. 6.12 shows that when D is higher, so is the $P(V_x \leq 0)$ at the cavity center. Moreover, the TKE at the cavity center close to the bed is higher at lower D for the same L/D (Fig. 6.13).

The PIV measurements also demonstrate that the flow field near the cavity corner (PL02) is more conducive to particle entrainment than the centerline plane (PL01) due to the absence of a recirculation vortex and higher V_y in the former, despite PL01 having a substantially higher TKE than PL02.

POD analysis of the vector data reveals that at lower D , the dominant modes comprising of large-scale (LS) eddies have lower contribution to the overall TKE of the flow field than the dominant modes at higher D (refer Table 6.4 and Figs. 6.24 - 6.27). This is most likely due to the size of the large-scale eddies being limited in the vertical direction by the flow depth (H). Thus, although D is lower and consequently less energy is required to lift the particle to the cavity top, the energy supplied by the LS eddies to the particle is also lower. This must have led to the higher deviations in SP6 curves of Fig. 6.22 as SP6 is also the most difficult to be entrained due to its lowest τ^* value.

7.2 Present study vs. grade control structures

Although light weight particles are used in the experimental study in contrast to stones in grade control structures, the experimental results obtained are still applicable to the real

world grade control structures. This is because, for sediment transport similarity, Shields' parameter similarity between the particles used in the experiments and stones used in the grade-control structures will suffice, irrespective of the usage of light weight particles in the study. This is limited to the condition that other test conditions – flow and cavity geometry, etc., remain the same. This aspect of the present study is elaborated by the following example and calculation. Using the subscript 'exp' for the experimental study and 'GCS' for the grade-control structures, Shields' parameter similarity gives:

$$\frac{u_{*exp}^2}{(s_{exp} - 1)d_{exp}} = \frac{u_{*GCS}^2}{(s_{GCS} - 1)d_{GCS}} \quad (7.1)$$

where u_* , s , and d represent the free-stream shear velocity, specific gravity of the particle, and diameter of the particle, respectively. The above equation can be written as:

$$\left(\frac{u_{*exp}}{u_{*GCS}}\right)^2 = \frac{(s_{exp} - 1)d_{exp}}{(s_{GCS} - 1)d_{GCS}} \quad (7.2)$$

In the experiments, s_{exp} ranges from 1.011 – 1.2, so $s_{exp} = 1.2$ corresponding to the SP6 particle is used in this example hereafter. Also, stones in general which are used in the grade-control structures have specific gravity $s_{GCS} = 2.3 - 2.8$, so $s_{GCS} = 2.5$ is taken and these two specific gravities are put in Eqn. 7.2, to obtain the following.

$$\left(\frac{u_{*exp}}{u_{*GCS}}\right)^2 = \frac{(1.2 - 1)d_{exp}}{(2.5 - 1)d_{GCS}} \quad (7.3)$$

$$\Rightarrow \left(\frac{u_{*exp}}{u_{*GCS}}\right)^2 = \left(\frac{1}{7.5}\right)\left(\frac{d_{exp}}{d_{GCS}}\right) \quad (7.4)$$

Putting $d_{exp} = 0.63$ cm which is the diameter for the SP6 particle and $d_{GCS} = 10$ cm for a typical stone particle used in the grade-control structures, we get

$$\left(\frac{u_{*exp}}{u_{*GCS}}\right)^2 = \left(\frac{1}{7.5}\right)\left(\frac{0.63}{10}\right) \quad (7.5)$$

$$\Rightarrow u_{*GCS} = 10.9u_{*exp} \quad (7.6)$$

Thus, it can be seen that if u_{*exp} is able to entrain SP6 particles with the given particle diameter and density, u_{*GCS} needs to be 10.9 times u_{*exp} to entrain stones with diameter = 10 cm and density = 2.5 g/cc. This is provided that all other cavity and flow conditions remain the same. Thus, scale effects are taken into account by the Shields' parameter similarity. However, it is to be mentioned that the cavity used in the experiment is a very simplified version of the entire grade-control structure which is in fact a network of cavities, and not just an individual isolated cavity. Still, the experimental results provide valuable information about the entrainment process which is fundamental and common to both the experiment and the grade-control structure.

7.3 Limitations of the study

One of the main aspects of this study is to investigate particle entrainment from a rectangular cavity, which is motivated by the grade control structures in Taiwan. The study aims to examine the fundamental mechanism of the entrainment phenomenon by which a particle is able to entrain from a cavity whose depth is several times higher than the particle diameter. Accordingly, the experimental setup was made to suit this need and not to replicate a model grade control structure, which is a more intricate structure as also mentioned in the preceding section. However, results obtained are helpful when further studies are conducted on real world grade control structures.

Apart from this, the experimental study has a large d/h ratio which although closely resembles the grade control structures, makes the experimental results less applicable to sand bed streams and more relevant to pebble or boulder streams. Furthermore, considering that the particles used are all spherical whereas pebble bed streams are likely to have angular pebbles or non-spherical pebbles as well, the entrainment is believed to be easier in the present study as spherical particles are more mobile and tend to have higher lift force.

Regarding the role of large-scale (LS) and small-scale (SS) eddies in the entrainment process, their individual effect on the entrainment process is not studied, and rather their role in entraining a particle is considered in unison. This may be slightly different from the exact case since SS eddies are considered to be more random than the growth and passage of LS eddies in the flow.

Apart from the above limitations, although a wide range of particle properties, cavity dimensions, and flow properties are used in the experimental study, there is always scope for using an even more extensive range of the variable to more accurately quantify the observations and results.

7.4 Recommendations

From all the experimental results presented in Chapters 4 - 6, it is clear that particle entrainment from a rectangular cavity is vastly different and remarkably more complex when compared to entrainment on a flat sediment bed. The most distinguishing factor separating these two phenomena is that the flow field inside the cavity is highly unsteady whereas in the free-stream region, the flow is more quiescent, steady and uniform. Clearly, the cavity flow field can be unidirectional, two-directional, or 3-dimensional with significant secondary flow and presence of large scale eddies. Entrainment of a particle subjected to such a varying flow field is thus intricately dependent on the cavity geometry, the free-stream flow configuration and the particle characteristics.

Hence, future studies can aim to formulate a model where these interdependencies between the free-stream flow parameters, cavity flow features and particle properties are rigorously quantified so as to predict the resultant entrainment probabilities for any specified test condition. Additionally, future studies can also use the free-stream flow depth (h) as a variable and integrate its effects in the entrainment model. Computational Fluid Dynamics (CFD) can also be used to conduct a parametric study of this entrainment phenomenon. However, care must be taken that sufficient grid points are used in the geometry mesh along with a transient solver so as to capture the time-variant and space-variant small scale and large scale eddies in the cavity flow field.

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APPENDIX 1

Entrainment time (t_e) of different particles (SP1 – SP6) for the 50 trials at different cavity depths (D) are presented in the following Tables A.1 to A.6, respectively. The following data corresponds to Fig. 4.8. Here, t_e is arranged in increasing order and NaN refers to trials when no entrainment was observed within 2 minutes (except SP6 particles where the maximum observation duration was 10 minutes). Here, t_e is in seconds and D is in mm.

Table A.1 (particle SP1)

Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$		Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$
1	3.58	3.5	5.41		26	6.38	8.69	28.35
2	3.86	3.7	5.79		27	6.58	8.9	33.21
3	3.91	3.76	6.1		28	6.63	8.97	34.91
4	4.12	3.91	6.79		29	7	9.04	35.1
5	4.4	4.39	6.95		30	7.46	9.32	35.7
6	4.41	4.46	6.99		31	7.47	9.79	37.1
7	4.86	4.5	7.12		32	7.62	9.81	37.3
8	4.93	4.6	7.36		33	7.67	9.92	40.23
9	5.11	4.73	8.74		34	7.73	10.2	47.6
10	5.12	4.8	8.92		35	8.06	10.52	47.96
11	5.16	4.91	9		36	8.1	10.88	55.8
12	5.18	5	9.57		37	8.37	11.62	56.14
13	5.18	5.33	10.54		38	8.39	12.01	64.04
14	5.36	5.55	11.93		39	8.67	12.17	99.37
15	5.43	5.65	11.95		40	8.74	12.6	105.42
16	5.55	5.95	13.11		41	8.83	12.81	152.56
17	5.78	6.17	13.66		42	9.24	13.2	NaN
18	5.81	6.36	13.72		43	9.43	15.62	NaN
19	5.82	6.73	17.47		44	9.91	15.79	NaN
20	5.9	6.74	18.01		45	10.1	16.57	NaN

21	5.98	6.84	19.22		46	10.63	17.99	NaN
22	6.02	6.99	21.54		47	10.64	18	NaN
23	6.2	7.16	21.66		48	10.81	18.48	NaN
24	6.24	7.36	24.04		49	10.97	21.21	NaN
25	6.31	7.72	27.64		50	17.7	22.14	NaN

Table A.2 (particle SP2)

Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$		Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$
1	3.12	3.12	9.74		26	9.09	14.06	66.48
2	3.19	3.14	10.66		27	9.19	14.37	66.65
3	3.28	3.29	10.79		28	9.2	14.54	78.67
4	3.35	3.87	13.39		29	9.32	14.92	84.83
5	3.63	4.56	15.6		30	9.42	15.54	88.83
6	4.22	4.65	15.65		31	9.46	15.87	93.2
7	4.4	5.09	20.35		32	10.36	15.9	133.73
8	4.7	5.24	20.48		33	10.46	17.41	NaN
9	4.9	6.08	24.31		34	10.58	17.62	NaN
10	5.45	6.16	24.62		35	11.24	17.7	NaN
11	5.5	7.06	25.29		36	11.29	19.8	NaN
12	5.6	7.7	25.4		37	11.35	20.82	NaN
13	6.86	8.04	25.92		38	11.96	21.1	NaN
14	7.06	8.54	27.33		39	12.01	22.48	NaN
15	7.07	9.2	27.73		40	12.9	23.06	NaN
16	7.26	9.91	29.41		41	12.96	24.77	NaN
17	7.58	9.95	34.9		42	13.13	26.11	NaN
18	7.64	10.01	36.94		43	13.9	26.72	NaN
19	7.94	10.02	39.62		44	14.23	30.64	NaN
20	8.06	10.69	41.34		45	16.64	36.48	NaN
21	8.43	10.74	45.62		46	18.62	37.2	NaN
22	8.78	10.8	49.12		47	19.44	38.51	NaN
23	8.89	12.01	54.08		48	19.81	41.39	NaN
24	8.99	12.62	61.93		49	28.68	47.59	NaN
25	9.07	12.86	66.38		50	37.19	48.99	NaN

Table A.3 (particle SP3)

Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$		Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$
1	3.43	3.21	12.61		26	12.78	18.69	52.32
2	3.58	4.64	16.7		27	13.24	18.93	53.93
3	4.89	4.81	21.11		28	13.57	19.85	56.45
4	5.48	5.1	22.24		29	13.64	20.36	56.76
5	6.12	5.72	23.41		30	14.11	20.43	64.36
6	6.54	5.84	23.99		31	14.18	20.86	68.24
7	6.56	6.58	26.37		32	14.63	21.16	73.4
8	6.88	8.56	27.18		33	14.92	21.9	81.73
9	8.7	9.13	28.92		34	14.96	21.9	NaN
10	8.91	9.37	29.18		35	15.73	21.92	NaN
11	9.31	11.08	29.56		36	16.4	23.51	NaN
12	9.33	11.9	30.84		37	16.5	24.46	NaN
13	10.04	11.98	31.58		38	17.46	24.99	NaN
14	10.49	12.05	31.59		39	18.52	25.19	NaN
15	10.93	12.2	32.02		40	18.66	25.58	NaN
16	11.06	12.36	33.23		41	19.98	26.7	NaN
17	11.11	13.3	34.47		42	21.87	29.42	NaN
18	11.37	14.55	38.44		43	22.22	29.53	NaN
19	11.38	15.16	41.07		44	22.83	30.63	NaN
20	11.63	15.18	42.62		45	23.27	30.92	NaN
21	11.63	15.43	43.56		46	24.4	32.24	NaN
22	11.76	15.58	44.15		47	25.83	32.32	NaN
23	11.8	15.68	44.95		48	28.71	32.48	NaN
24	11.98	16.11	44.99		49	29.43	34.55	NaN
25	12.44	17.93	49.33		50	31.47	35.98	NaN

Table A.4 (particle SP4)

Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$		Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$
1	3.5	5.79	10.96		26	14.98	19.93	64.7
2	6.24	6.08	13.8		27	14.98	20.42	76.03
3	7.34	9.11	19.61		28	15.83	20.54	NaN
4	7.93	10.68	21.3		29	15.98	21.33	NaN
5	8.23	11.92	21.39		30	16.22	21.63	NaN
6	8.32	12.34	24.11		31	16.48	21.78	NaN
7	8.4	13.1	25.28		32	17.6	23.23	NaN
8	8.56	13.94	25.32		33	17.73	23.23	NaN
9	8.98	14.56	25.81		34	18.44	24.61	NaN
10	9.28	14.66	28.04		35	19.5	25.88	NaN
11	10.58	14.9	32.73		36	19.99	26.17	NaN
12	10.69	15.59	35.06		37	20.3	27.59	NaN
13	11.62	16.12	35.31		38	22.11	27.9	NaN
14	12.06	16.23	36.03		39	23.33	28.04	NaN
15	12.14	16.31	38.4		40	24.06	28.09	NaN
16	12.3	16.75	40.51		41	24.81	28.6	NaN
17	12.75	17.35	42.91		42	25.37	29.43	NaN
18	12.75	17.41	43.88		43	25.88	35.38	NaN
19	13.35	18.13	44.08		44	28.2	38.57	NaN
20	13.91	18.15	44.53		45	30.01	38.76	NaN
21	14.12	18.41	52.41		46	31.18	41.87	NaN
22	14.41	18.72	52.64		47	33	42.73	NaN
23	14.64	18.88	55.32		48	34.18	48.2	NaN
24	14.75	18.91	55.88		49	36.62	49.74	NaN
25	14.78	19.56	62.49		50	37.57	51.46	NaN

Table A.5 (particle SP5)

Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$		Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$
1	5.72	10.32	14.5		26	35.87	40.73	145.12
2	13.08	11.24	21.12		27	36.06	41.63	201.18
3	13.29	14.8	22.25		28	37.38	44.67	204.71
4	13.54	17.13	26		29	38.67	46.1	230.13
5	14.58	17.53	35.62		30	47.94	50.49	NaN
6	14.65	17.74	35.79		31	52.7	54.24	NaN
7	16.39	18.82	40.14		32	53.05	54.26	NaN
8	17.9	19.32	46.04		33	53.94	54.62	NaN
9	18	21.31	46.92		34	55.51	57.45	NaN
10	18.09	21.45	51.28		35	59.33	58.9	NaN
11	18.11	23.36	55.92		36	62.46	59.78	NaN
12	19.93	23.48	60.82		37	62.58	60.59	NaN
13	21.04	23.71	66.27		38	66.38	60.87	NaN
14	22.86	24.88	80.1		39	76.34	61.01	NaN
15	23.41	27.74	89.21		40	77.77	65.5	NaN
16	24.01	30.85	99.11		41	81.5	67.85	NaN
17	24.96	33.84	99.53		42	84.86	68.5	NaN
18	25.79	34.26	101.21		43	86.82	81.14	NaN
19	25.83	34.32	110.72		44	87.35	81.57	NaN
20	26.62	34.37	111.95		45	92.13	89.33	NaN
21	29.16	37.21	115.96		46	113.26	94.58	NaN
22	32.56	37.68	116.54		47	123.4	98.12	NaN
23	33.67	37.94	127.13		48	129.78	120.74	NaN
24	33.76	38.05	135.2		49	147.06	137.68	NaN
25	34.51	40.59	141.61		50	172.7	143.21	NaN

Table A.6 (particle SP6)

Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$		Sl. no.	t_e $D=53$	t_e $D=65$	t_e $D=81$
1	9	21	57.87		26	135	204	NaN
2	11	37	61.75		27	135	217	NaN
3	15	50	96.94		28	149	244	NaN
4	20	62	118.43		29	161	258	NaN
5	27	71	134.38		30	165	267	NaN
6	28	77	137.25		31	165	273	NaN
7	31	78	168.04		32	182	292	NaN
8	32	81	173.46		33	200	292	NaN
9	41	84	185		34	230	310	NaN
10	44	88	186.13		35	231	333	NaN
11	47	98	242.54		36	234	353	NaN
12	63	100	258		37	241	359	NaN
13	64	104	269.88		38	327	431	NaN
14	84	111	282		39	329	446	NaN
15	85	112	465.23		40	333	451	NaN
16	86	116	601.1		41	339	455	NaN
17	88	130	NaN		42	363	461	NaN
18	90	132	NaN		43	385	507	NaN
19	90	133	NaN		44	414	515	NaN
20	90	140	NaN		45	502	517	NaN
21	99	188	NaN		46	523	NaN	NaN
22	100	189	NaN		47	553	NaN	NaN
23	106	191	NaN		48	571	NaN	NaN
24	117	193	NaN		49	584	NaN	NaN
25	121	198	NaN		50	NaN	NaN	NaN