# List of Figures

1.1 Subarnarekha River, Jharkhand, India. .................................................. 5

1.2 A series of “Current Crescents” around pebble barriers in a recent stream bed at Subarnarekha River. Most of the pebbles are covered by leaves and other plant materials carried by the stream. ................................................................. 5

2.1 Coordinates and sign convention used in the study ................................. 10

2.2 Time series of stream-wise velocity $u$, transverse velocity $v$ and vertical velocity $w$ in a turbulent flow ................................................................. 15

2.3 Transport of momentum due to turbulent velocity fluctuation .................. 20

2.4 Sketch of representative velocity profiles in open channel ....................... 23

2.5 Quadrant decomposition of turbulent events .......................................... 39

2.6 SonTek® 16 MHz 3-D Micro ADV. .......................................................... 41

2.7 3-D down-looking ADV probe used at FML. ........................................ 42

2.8 Schematic diagram of the sampling volume. .......................................... 42

3.1 The experimental channel of Fluvial Mechanics Laboratory at ISI, Kolkata. . 52

3.2 The schematic diagram of the experimental channel of Fluvial Mechanics Laboratory. (a) Plan view, (b) Front view ......................................................... 53

3.3 Electro-magnetic discharge meters ......................................................... 54

3.4 Schematic diagram of the experimental set-up ......................................... 55
3.5 Mean velocity profiles over plane sand bed: + for $\frac{v}{u_*}$, ◦ for $\frac{w}{u_*}$ and * for $\frac{w}{u_*}$.

3.6 Side view of obstacles of different cylinder diameters: (a1) for 7.0cm, (a2) for 6.0cm, (a3) for 5.8cm, (a4) for 5.0cm, (a5) for 4.2cm, (a6) for 3.2cm, (a7) for 2.6cm and (a8) for 2.0cm.

3.7 Plan view of obstacles of different diameters.

4.1 Mean velocity profiles (a) for $Re = 1.5 \times 10^5$ and (b) for $Re = 3.0 \times 10^5$. Symbols, ◦, stream-wise velocity and *, vertical velocity. Solid lines represent log-law.

4.2 Stream-wise turbulence intensity profiles (a) for $Re = 1.5 \times 10^5$ and (b) for $Re = 5.0 \times 10^5$.

4.3 Vertical turbulence intensity profiles (a) for $Re = 1.5 \times 10^5$ and (b) for $Re = 3.0 \times 10^5$.

4.4 Reynolds Shear stress profiles (a) for $Re = 1.5 \times 10^5$ and (b) for $Re = 3.0 \times 10^5$.

4.5 Evolution over time of scour hole around cylinder of diameter ($D_c = 3.2$cm) for discharge $Q = 0.015$ m$^3$/sec.

4.6 The equilibrium scour holes developed at the upstream of three different cylinders of diameters ($D_c = 3.2$cm, 4.2cm and 6.0cm) for $Q = 0.015$ m$^3$/sec.

4.7 Observed and computed profiles at the location A for all three diameters of cylinders: (a) velocity profiles in log and linear scales, (b) stream-wise turbulence intensity, (c) vertical turbulence intensity profiles. Solid line represents fitted profiles, and * represents observed data. Three bottom most points on turbulence intensities are omitted during fitting.
4.8 Stream-wise mean velocity profiles over the scour marks generated from different cylinders; vertical dotted lines and the solid curved lines represent the reference line (zero line) and velocity profiles respectively for $Q = 0.015 \, m^3/\text{sec}$; for $D_c = 3.2\text{cm}$  

4.8 (Continued; for $D_c = 4.2\text{cm}$)  

4.8 (Continued; for $D_c = 6.0\text{cm}$)  

4.9 Vertical mean velocity profiles over the scour marks generated from different cylinders; vertical dotted lines and the solid curved lines represent the reference line (zero line) and velocity profiles respectively for $Q = 0.015 \, m^3/\text{sec}$; for $D_c = 3.2\text{cm}$  

4.9 (Continued; for $D_c = 4.2\text{cm}$)  

4.9 (Continued; for $D_c = 6.0\text{cm}$)  

4.10 Mean velocity vector plots along the surface of the scour marks for all three cases for $Q = 0.015 \, m^3/\text{sec}$; for $D_c = 3.2\text{cm}$  

4.10 (Continued; for $D_c = 4.2\text{cm}$)  

4.10 (Continued; for $D_c = 6.0\text{cm}$)  

4.11 Vertical profiles of stream-wise turbulence intensity along the surface of scour marks for all three different diameters of cylinders for $Q = 0.015 \, m^3/\text{sec}$; for $D_c = 3.2\text{cm}$  

4.11 (Continued; for $D_c = 4.2\text{cm}$)  

4.11 (Continued; for $D_c = 6.0\text{cm}$)  

4.12 Vertical profiles of vertical turbulence intensity along the surface of scour marks for all three different diameters of cylinders for $Q = 0.015 \, m^3/\text{sec}$; for $D_c = 3.2\text{cm}$  

4.12 (Continued; for $D_c = 4.2\text{cm}$)
4.12 (Continued; for $D_c = 6.0\text{cm}$) .......................................................... 89

4.13 Reynolds shear stress $-\rho u'w'$ along the flow over the scour marks for all three cylinder diameters for $Q = 0.015 \text{m}^3/\text{sec}$; for $D_c = 3.2\text{cm}$ ............................... 90

4.13 (Continued; for $D_c = 4.2\text{cm}$) .......................................................... 91

4.13 (Continued; for $D_c = 6.0\text{cm}$) .......................................................... 92

4.14 Reynolds shear stress along the flow at the bottom in the scoured region and at the bed level (zero level). Solid line represents for bottom shear stress ($\tau_0$) and dotted line represents for shear stress at the bed level ($\tau_{0bl}$) for Reynolds number $Re = 6.76 \times 10^4$. .......................................................... 94

4.15 Plot of dimensionless scour-width $w_s/L$ vs. sediment Froude number $F_s$ for different cylinder diameters ($D_c = 2.0\text{cm (□)}, 2.6\text{cm (*)}, 3.2\text{cm (o)}, 4.2\text{cm (+)}, 5.0\text{cm (×)}, 5.8\text{cm (○)}, 6.0\text{cm (▽)}$ and 7.0cm (◇)) ................................. 95

4.16 Schematic diagrams of equilibrium scour marks with sampling locations A to $H$ for the cylinder diameter $D_c = 3.2, 4.2, 6.0\text{ cm.}$ ...................................................... 96

4.17 Profiles of the kinetic energy $\frac{\rho}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$ of turbulent fluctuation over the scour marks generated from different cylinders of diameters ($D_c = 3.2, 4.2$ and 6.0cm); vertical solid lines and the dotted curved lines represent the reference line (zero line) and kinetic energy profiles respectively, at exact locations A, B, C, D, E, F, G and H shown in Fig. 4.16; for $D_c = 3.2\text{cm}$ ........................................ 97

4.17 (Continued; for $D_c = 4.2\text{cm}$) .......................................................... 98

4.17 (Continued; for $D_c = 6.0\text{cm}$) .......................................................... 99

xiv
4.18 Profiles of the turbulent diffusion \((u^2w)\) in longitudinal direction over the scour marks generated from different cylinders of diameters \((D_c = 3.2, 4.2\) and \(6.0\) cm); vertical solid lines and the dotted curved lines represent the reference line (zero line) and turbulent diffusion profiles respectively, at exact locations A, B, C, D, E, F, G and H shown in Fig. 4.16; for \(D_c = 3.2\) cm.

4.18 (Continued; for \(D_c = 4.2\) cm)

4.18 (Continued; for \(D_c = 6.0\) cm)

4.19 Profiles of the turbulent diffusion \((uw^2)\) in vertical direction over the scour marks generated from different cylinders of diameters \((D_c = 3.2, 4.2\) and \(6.0\) cm); vertical solid lines and the dotted curved lines represent the reference line (zero line) and turbulent diffusion profiles respectively, at exact locations A, B, C, D, E, F, G and H shown in Fig. 4.16; for \(D_c = 3.2\) cm.

4.19 (Continued; for \(D_c = 4.2\) cm)

4.19 (Continued; for \(D_c = 6.0\) cm)

4.20 Distributions of the skewness of \(u\) against \(z/h\) at locations A to H over the scour holes for +, \(D_c = 3.2\) cm; ◦, \(D_c = 4.2\) cm; ⊲, \(D_c = 6.0\) cm.

4.21 Distributions of the skewness of \(w\) against \(z/h\) at the locations A to H over the scour holes for +, \(D_c = 3.2\) cm; ◦, \(D_c = 4.2\) cm; ⊲, \(D_c = 6.0\) cm.

4.22 Distributions of the stream-wise flux of turbulent kinetic energy at locations A to H over the scour holes for +, \(D_c = 3.2\) cm; ◦, \(D_c = 4.2\) cm; ⊲, \(D_c = 6.0\) cm.

4.23 Distributions of the vertical flux of turbulent kinetic energy at locations A to H over the scour holes for +, \(D_c = 3.2\) cm; ◦, \(D_c = 4.2\) cm; ⊲, \(D_c = 6.0\) cm.
4.24 Plots of stress fraction $S_{i,H}$ ($i=1, 2, 3, \text{ and } 4; H = 0, 8, \text{ and } 16$) against depth $z/h$. $\circ$, outward interactions ($Q_1$); $\square$, ejections ($Q_2$); $\triangleright$, inward interactions ($Q_3$); $+$, sweep ($Q_4$). ... 116

4.25 Plots of ratios $R_{i,H}$ ($i=1$ and 2; $H=0, 1$ and 3) against $z/h$. $\circ$, $R_{1,H}$; $\ast$, $R_{2,H}$. 117

4.26 Plots of $E_H$ against hole size $H$ for $D_c = 3.2$cm. (a) At the location $A$: $\circ$, $z/h = 0.018$; $+$, $z/h = 0.158$; $\triangleright$, $z/h = 0.269$, and (b) at the location $D$ (close to the cylinder: $\circ$, $z/h = -0.080$; $+$, $z/h = 0.018$; $\triangleright$, $z/h = 0.269$. ... 118

4.27 Plots of $E_H$ against hole size $H$ at the bed level surface $z/h = 0.018$. (a) At the location $A$: $\circ$, $D_c = 3.2$cm; $+$, $D_c = 4.2$cm; $\triangleright$, $D_c = 6.0$cm, and (b) at location $D$ close to the cylinder: $\circ$, $D_c = 3.2$cm; $+$, $D_c = 4.2$cm; $\triangleright$, $D_c = 6.0$cm. ... 119

4.28 Depth averaged stress fractions $|S_{i,0}|$ against $x/h$ for different diameters of cylinders at the locations A, B, C, D, E, F, G and H with the location A starting from the first point of the figures (a), (b), (c). $\circ$, Outward interaction; $\square$, Ejection; $+$, Inward interaction; $\triangleright$, Sweep. ... 120

4.29 Stress fractions $S_{i,H}$ against hole size $H$ at location $A$ for $D_c = 3.2$cm. $\circ$, $z/h = 0.018$; $+$, $z/h = 0.158$; $\triangleleft$, $z/h = 0.269$. ... 122

4.30 Stress fractions $S_{i,H}$ against hole size $H$ at D for $D_c = 3.2$cm. $\circ$, $z/h = -0.080$; $+$, $z/h = 0.018$; $\triangleright$, $z/h = 0.269$. ... 123

4.31 Stress fractions $S_{i,H}$ against hole size $H$ at location A for $z/h = 0.018$ (zero level). $\circ$, $D_c = 3.2$cm; $+$, $D_c = 4.2$cm; $\triangleleft$, $D_c = 6.0$cm. ... 124

4.32 Stress fractions $S_{i,H}$ against hole size $H$ at location D for $z/h = 0.018$ (zero level). $\circ$, $D_c = 3.2$cm; $+$, $D_c = 4.2$cm; $\triangleleft$, $D_c = 6.0$cm. ... 125

4.33 Plots of $T_{i,H}$ ($i = 1, 2, 3, \text{ and } 4; H = 0.0, 0.2, \text{ and } 0.6$) against $z/h$. $\circ$, outward interactions ($Q_1$); $\square$, ejections ($Q_2$); $\ast$, inward interactions ($Q_3$); $+$, sweep ($Q_4$). 127
4.34 Plots of $P_{i,H}$ ($i = 1, 2, 3, \text{ and } 4; H = 0.0, 0.2, \text{ and } 0.6$) against $z/h$. ◦, outward interaction ($Q_1$); □, ejection ($Q_2$); △, inward interaction ($Q_3$); +, sweep ($Q_4$).

4.35 Profiles of the time fraction ($T_{i,0}$) of bursting event in the $i^{th}$ quadrant over the scour marks generated from different cylinders of diameters ($D_c = 3.2, 4.2$ and 6.0cm); vertical solid lines and * represent the reference line (zero line) and time fraction profiles respectively, exact locations A, B, C, D, E, F, G and H shown in Fig. 4.16.

4.36 Profiles of the probability ($P_{i,0}$) of bursting event occurred in the $i^{th}$ quadrant over the scour marks generated from different cylinders of diameters ($D_c = 3.2, 4.2$ and 6.0cm); vertical solid lines and * represent the reference line (zero line) and probability profiles respectively, exact locations A, B, C, D, E, F, G and H shown in Fig. 4.16.

4.37 $T_{1,0}$ vs. $T_{2,0}$(*) and $T_{4,0}$(+) from three different cylinders of diameters ($D_c = 3.2, 4.2$ and 6.0cm); vertical solid lines and symbols (*, +) represent the estimated and observed profiles respectively, at exact locations A, B, C, D, E, F, G and H shown in Fig. 4.16.

4.38 $T_{3,0}$ vs. $T_{2,0}$(*) and $T_{4,0}$(+) from three different cylinders of diameters ($D_c = 3.2, 4.2$ and 6.0cm); vertical solid lines and symbols (*, +) represent the estimated and observed profiles respectively, at exact locations A, B, C, D, E, F, G and H shown in Fig. 4.16.

4.39 $P_{1,0}$ vs. $P_{2,0}$(*) and $P_{4,0}$(+) from three different cylinders of diameters ($D_c = 3.2, 4.2$ and 6.0cm); vertical solid lines and symbols (*, +) represent the estimated and observed profiles respectively at exact locations A, B, C, D, E, F, G and H shown in Fig. 4.16.
4.40 $P_{3,0}$ vs. $P_{2,0}(\ast)$ and $P_{4,0}(\mp)$ from three different cylinders of diameters ($D_c = 3.2, 4.2$ and $6.0$cm); vertical solid lines and symbols ($\ast, \mp$) represent the estimated and observed profiles respectively, at exact locations A, B, C, D, E, F, G and H shown in Fig. 4.16.

4.41 Sketch of the three planes and four quadrants in the $(u', v')$, $(u', w')$ and $(v', w')$ planes.

4.42 Schematic division of the coherent phenomenon in $xy$-plane.

4.42 (Continued)

4.43 Plots of stress fractions $S_{i,H}$ against hole size $H$ at bottom label for $D_c = 4.2$ cm. (a) At the location $A$: $\circ$, $xy$-plane; $+$, $xz$-plane; $\triangleright$, $yz$-plane, (b) at $D$ close to the cylinder: $\circ$, $xy$-plane; $+$, $xz$-plane; $\triangleright$, $yz$-plane and (c) at $H$: $\circ$, $xy$-plane; $+$, $xz$-plane; $\triangleright$, $yz$-plane.

4.44 Plots of stress fractions $S_{i,H}$ against hole size $H$ at $z/h = 0.50$ for $D_c = 4.2$ cm. (a) At the location $A$: $\circ$, $xy$-plane; $+$, $xz$-plane; $\triangleright$, $yz$-plane, (b) at $D$ close to the cylinder: $\circ$, $xy$-plane; $+$, $xz$-plane; $\triangleright$, $yz$-plane and (c) at $H$: $\circ$, $xy$-plane; $+$, $xz$-plane; $\triangleright$, $yz$-plane.

4.45 Depth averaged stress fractions $|S_{i,0}|(i = 1, 2, 3, 4)$ against $x/h$ for different planes at the locations A, B, C, D, E, F, G and H with the location A starting from the first point of the figures (a), (b), (c). $\circ$, $i = 1$; $\square$, $i = 2$; $+$, $i = 3$; $\triangleright$, $i = 4$.

4.46 Longitudinal averaged stress fractions $|S_{i,0}|(i = 1, 2, 3, 4)$ for different planes at the all locations(A, B, C, D, E, F, G and H).

5.1 Joint probability density function $p(\hat{u}, \hat{w})$ of fluctuating velocity components $(u', w')$ at the location D shown in Fig. 4.16.
5.1 (Continued) ................................................................. 156

5.1 (Continued) ................................................................. 157

5.2 Contour plots of joint probability density function \( p(\hat{u}, \hat{w}) \) at three different heights at the location \( A \) on the smooth surface for the case \( D_c=3.2 \text{cm} \) .................................................. 158

5.3 Contour plots of joint probability density function \( p(\hat{u}, \hat{w}) \) at three different heights at the location \( D \) (close to the cylinder) within the scour region generated by the cylinder diameter \( D_c=3.2 \text{cm} \) .................................................. 159

5.4 Contour plots of \( p(\hat{u}, \hat{w}) \) for three different cylinder diameters \( (D_c=3.2, 4.2 \text{ and } 6.0 \text{cm}) \) at the location \( A \) (smooth surface) at the level surface \( z/h = 0.018 \) .................................................. 160

5.5 Contour plots of \( p(\hat{u}, \hat{w}) \) at three different cylinder diameters \( (D_c=3.2, 4.2 \text{ and } 6.0 \text{cm}) \) at the location \( D \) (scour region, close to the cylinder) at the bed level surface \( z/h = 0.018 \) .................................................. 161

5.6 Joint probability density function \( p(\hat{u}, \hat{w}) \) at eight different locations \( A \) to \( H \) along the flow for \( D_c=3.2 \text{cm} \) at the bed surface .................................................. 163

5.6 (Continued) ........................................................................ 164

5.7 Contour plots of \( p(\hat{u}, \hat{w}) \) at eight different locations \( A \) to \( H \) along the flow for \( D_c=3.2 \text{cm} \) at the bed surface .................................................. 166

5.8 Plots of \( p(\hat{u}) \) against \( \hat{u} = u'/\sigma_u \) for \( D_c=3.2 \text{cm} \). (a) At the location \( A \) (smooth surface): \( \circ (\ldots), z/h = 0.018; + (- -), z/h = 0.158; \triangleright (-), z/h = 0.269 \); and (b) at the location \( D \) (scour region): \( \circ (\ldots), z/h = -0.080; + (- -), z/h = 0.018; \triangleright (-), z/h = 0.269 \). Here dot, dash and solid lines represent the theoretical value. 167
5.9 Plots of $p(\hat{u})$ against $\hat{u} = u'/\sigma_u$ at the bed level $z/h = 0.018$. (a) At the location $A$ (smooth surface): ◦ (....), $D_c = 3.2cm$; + (- -), $D_c = 4.2cm$; ▷ (-), $D_c = 6.0cm$, and (b) At location D (scoured region) ◦ (....), $D_c = 3.2cm$; + (- -), $D_c = 4.2cm$; ▷ (-), $D_c = 6.0cm$. Here dot, dash and solid lines represent the theoretical value.

5.10 Plots of $p(\hat{w})$ against $\hat{w} = w'/\sigma_w$ for $D_c = 3.2cm$. (a) At the location $A$ (smooth surface): ◦ (....), $z/h = 0.018$; + (- -), $z/h = 0.158$; ▷ (-), $z/h = 0.269$; and (b) at the location D (scour region): ◦ (....), $z/h = -0.080$; + (- -), $z/h = 0.018$; ▷ (-), $z/h = 0.269$. Here dot, dash and solid lines represent the theoretical value.

5.11 Plots of $p(\hat{w})$ against $\hat{w} = w'/\sigma_w$ at the bed level $z/h = 0.018$. (a) At the location $A$ (smooth surface): ◦ (....), $D_c = 3.2cm$; + (- -), $D_c = 4.2cm$; ▷ (-), $D_c = 6.0cm$, and (b) at the location D: ◦ (....), $D_c = 3.2cm$; + (- -), $D_c = 4.2cm$; ▷ (-), $D_c = 6.0cm$. Here dot, dash and solid lines represent the theoretical value.

5.12 Plots of $p_{\tau_n}(\tau_n)$ against $\tau_n$ for $D_c = 3.2cm$. (a) At $A$ on the smooth surface: ◦ (- -), $z/h = 0.018$; + (- -), $z/h = 0.158$; ▷ (-), $z/h = 0.269$, and (b) at $D$ (close to the cylinder) within the scour region: ◦ (- -), $z/h = -0.080$; + (- -), $z/h = 0.018$; ▷ (-), $z/h = 0.269$. Here dash-dot, dash and solid lines represent the theoretical value.

5.13 Plots of $p_{\tau_n}(\tau_n)$ against $\tau_n$ at the level surface $z/h = 0.018$. (a) At the location $A$: ◦ (- -), $D_c = 3.2cm$; + (- -), $D_c = 4.2cm$; ▷ (-), $D_c = 6.0cm$, and (b) at the location $D$: ◦ (- -), $D_c = 3.2cm$; + (- -), $D_c = 4.2cm$; ▷ (-), $D_c = 6.0cm$. Here dash-dot, dash and solid lines represent the theoretical value.
5.14 Plots of stress fractions $S_{i,H}$ against hole size $H$ for $D_c = 3.2\text{cm}$. (a) At the location $A$: ◦ ($\cdot - $), $z/h = 0.018$; + (- -), $z/h = 0.158$; □ (-), $z/h = 0.269$, (b) at $D$ close to the cylinder: ◦ ($\cdot - $), $z/h = -0.080$; + (- -), $z/h = 0.018$; □ (-), $z/h = 0.269$ and (c) at $H$: ◦ ($\cdot - $), $z/h = 0.041$; + (- -), $z/h = 0.158$; □ (-), $z/h = 0.269$. Here dash-dot, dash and solid lines represent the theoretical value.

5.15 Plots of stress fractions $S_{i,H}$ against hole size $H$ at the level surface $z/h = 0.018$. (a) At the location $A$: ◦ ($\cdot - $), $D_c = 3.2\text{cm}$; + (- -), $D_c = 4.2\text{cm}$; □ (-), $D_c = 6.0\text{cm}$, and (b) at $D$: ◦ ($\cdot - $), $D_c = 3.2\text{cm}$; + (- -), $D_c = 4.2\text{cm}$; □ (-), $D_c = 6.0\text{cm}$. Here dash-dot, dash and solid line represent the theoretical value.

5.16 Plots of $p_j(\tau_j); j = 1, 2, 3$ against $\tau_j; j = 1, 2, 3$ at height $z/h = 0.192$ for $D_c = 4.2\text{cm}$. (a) At the location $A$: ◦ ($\cdot - $), $xy$-plane; + (- -), $xz$-plane; □ (-), $yz$-plane, (b) at $D$ close to the cylinder: ◦ ($\cdot - $), $xy$-plane; + (- -), $xz$-plane; □ (-), $yz$-plane and (c) at $H$: ◦ ($\cdot - $), $xy$-plane; + (- -), $xz$-plane; □ (-), $yz$-plane. Here dash-dot, dash and solid lines represent the theoretical value.

5.17 Plots of stress fractions $S_{i,H}$ against hole size $H$ at height $z/h = 0.192$ for $D_c = 4.2\text{cm}$. (a) At the location $A$: ◦ ($\cdot - $), $xy$-plane; + (- -), $xz$-plane; □ (-), $yz$-plane, (b) at $D$ close to the cylinder: ◦ ($\cdot - $), $xy$-plane; + (- -), $xz$-plane; □ (-), $yz$-plane and (c) at $H$: ◦ ($\cdot - $), $xy$-plane; + (- -), $xz$-plane; □ (-), $yz$-plane. Here dash-dot, dash and solid lines represent the theoretical value.