

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**FLOW AND TURBULENCE STRUCTURE AROUND INCLINED EMERGENT
ISOLATED CYLINDER UNDER STEADY CONDITIONS**

M.Sc. THESIS

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Department of Coastal Sciences and Engineering

Coastal Sciences and Engineering Programme

JANUARY 2015

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**KARARLI AKIM KOŞULARINDA AKIMA BATMAMIŞ TEKİL EĞİK
SİLİNDİR ÇEVRESİNDE AKIM VE TÜRBÜLANS YAPISI**

YÜKSEK LİSANS TEZİ

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To my family,

FOREWORD

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ABBREVIATIONS

α	: Angle of V- notch Crest
β	: Angle of attack
δ	: Thickness of Boundary Layer
θ	: Inclination Angle
μ	: Dynamic Viscosity
ν	: Kinematic Viscosity
ρ	: Density of Water
A	: Area
ADV	: Accoustic Doppler Velocity
b	: Channel Width
C_D	: Drag Force Coefficient
C_{wt}	: Triangular Weir Coefficient
D	: Diameter of Cylinder
F_v	: The Frequency of Vortex Shedding
F_D	: Drag Force
g	: Acceleration of Gravity
H	: High of Free Stream Surface above of Crest
k	: Turbulence Kinetic Energy
Q	: Cross Sectional Discharge of Flow
Re	: Reynolds Number
Re_D	: Reyonlds Number over a Cylinder
T	: Time
U	: Streamwise Velocity
$\bar{u}$	: Time Avreaged of Streamwise Velocity
u'	: Flactuation of Streamwise Velocity
X_s	: Separation Distance

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FLOW AND TURBULENCE STRUCTURE AROUND INCLINED EMERGENT ISOLATED CYLINDER UNDER STEADY CONDITIONS

SUMMARY

Due to increase of world population and level of public welfare, an increment need to natural resources and their access methods are observed. Performed tests are indirect endeavors to achieve this purpose. The developed model can be assumed as bridge piers and legs of offshore platforms and offshore wind turbines.

The aim of these experiments is to detect the influence of the cylindrical structure with a smooth surface, on separation distance, boundary layer and wake region over the circular cylinder, turbulence and vortex components and their changing manner.

All the experiments were conducted in the open channel flow with the size of 18m length, 0.5m width and 0.5m depth. At this case of study four inclined cylinders and upstanding case were studied. Each case contained three discharges ($Q_1 = 47 \text{ lt/s} > Q_2 = 17 \text{ lt/s} > Q_3 = 7 \text{ lt/s}$) and the Reynolds number are in the subcritical regime ($300 < Re < 3 \times 10^5$). Both of Eulerian approach and Lagrangian approach as measuring the flow velocities by one ADV flow velocities were measured and flow visualization were observed by laser sheet

The experimental data were analyzed after despiking. Velocity components, turbulence intensities, turbulence kinetic energy and mean kinetic energy were calculated as a non-dimensional parameter. Time average and Reynolds decomposition methods used for derived of three dimensional instantaneous velocity value as mean velocity and fluctuation part of flow velocity. The data are made dimensionless, using the approach undisturbed velocity, V_{un} , local flow depth, z_0 , and diameter of cylinder, D . By the results of experimental findings the following facts revealed

By the effect of higher Reynolds number the core of separation distance of downstream extended. The magnitude of vertical time-average velocity increased due to the increase of inclination angle. The highest turbulent kinetic energy regions were observed for the vertical cases and by the effect of inclination the turbulent kinetic energy decreases In fact the lower turbulent kinetic energy at the inclination case of cylinder related to more hydrodynamic form as much as vertical case and increasing of submerged volume of cylinder. As result of flow visualization, the highest separation distance at the upstream of cylinder was observed at lowest Reynolds number of vertical case. This means separation was delayed as the influence of higher Reynolds number and separation distance decreased due to increase of inclination.

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ÖZET

Boru etrafında oluşan akım, gerek inşaat gerekse de makina mühendisliğinin temel konularından biri olup, uygulama aşamasında anlaşılması gereken son derece önemli bir konu olarak karşımıza çıkar. Daha açık şekilde ifade etmek gerekirse, mühendislik alanında konu ile ilgili uygulamaların başarıya ulaşması, büyük ölçüde boru etrafında meydana gelen düzenli ikincil akımların son derece detaylı şekilde anlaşılmasını zorunlu kılar. Son otuz yılda konuyla ilgili gerçekleştirilen araştırmalar ve sayısal modeller sayesinde konu hakkında önemli bir bilgi birikimine ulaşılmıştır. Ancak bununla birlikte, yapılan çalışmalar problemin sözkonusu karmaşık yapısını belirli bir noktaya kadar aydınlatmış olmakla birlikte konu ile ilgili halen bazı noktalarda bilgi boşluğu bulunmaktadır.

Bu çalışma kapsamında özellikle açık deniz platformlarında, açık deniz rüzgar türbinlerinde, kıyı korumada kullanılan dalga perdesi uygulamalarında, köprü ayaklarında, ve bazı durumlarda da çevresel hidrolik problemlerinde karşımıza çıkan “akıma maruz kalan eğik silindir etrafındaki akım” problemi ele alınmıştır.

Konunun araştırılması için deneysel çalışmalar gerçekleştirilmiştir. Deneysel çalışma, İstanbul Teknik Üniversitesi, Hidrolik Laboratuvarı’nda yapılmıştır. 18 m uzunluğunda, 0.5 m genişliğinde ve 0.5 m derinliğinde bir açık akım kanalında yürütülen deneylerde farklı akım koşulları altında dik, 15, 30, 40 ve 50 derece eğime sahip tekil silindirler etrafındaki akım koşulları konumsal olarak yoğun hız ölçümleri ile araştırılmıştır. Buradan hareketle taban yakınında silindir membaında meydana gelen ayrılma kökenli atnalı çevrintileri ile yüzüye yakın kısımda ters basınç gradyanları neticesinde gelişen yüzeysel çevrintilerin etkileşimi Eularian yaklaşım ile yorumlanmıştır. Permanan bir akım koşulunda üç farklı debi ($Q_1 = 47 \text{ lt/s} > Q_2 = 17 \text{ lt/s} > Q_3 = 7 \text{ lt/s}$) ve beş değişik açığa sahip bir boru üzerinde yapılan bir çalışmada esnek uçlu bir ADV aracılığıyla ölçümler gerçekleştirilmiş ve problemin Laser Sheet ile Lagrangian olarak da araştırılması hedeflenmiştir. ADV kullanarak borunun belirli bir mesafesinde hem manba hem mansap kısımlarında üç boyutlu hız profilleri alınmıştır. Akım görselleştirme işlemleri yalnız

borunun menba tarafında yapılmıştır. ADV ile alınan hız profilleri 100 Hz örnekleme sıklığı ile ölçülmüş olup ve örnekleme süresi 90 saniyedir.

Daha önceki yapılmış çalışmalarda, deney sırasında kaynağı belli olmayan nedenlerle ADV ile kaydedilen üç boyutlu hız profilleri aykırı değerler gözlemlenmiştir. Bu kirlenmiş değerleri temizlemeden kullanmak yanlış bir sonuca varmaya yol açar. Bu yüzden çalışmada da verilerin önışlenmesi aşamasında bu aykırı değerler özel bir yöntemle filtre edilmiştir.

Analizin ilk aşamasında zamansal hız ortalamaları hesaplanmıştır. Sonraki aşamada hız verileri ortalama ve çalkantı bileşenleri olarak ikiye ayrılmış, ve bu neticeyle türbülans kinetik enerji ve zamansal ortalama kinetik enerji hesaplanmıştır. Bu şekilde yapı civarında oluşan ikincil akımların silindirin eğikliğine bağılı olarak nasıl değıştiğı sonuçlar kısmında detaylı olarak tartışılmıştır. Akım görselleme işlemlerinden silindirin menba kısmında ayrılma mesafesi hesaplanmıştır.

Analizlerden elde edilmiş sonuçlara bağılı olarak silindirin arka tarafında meydana gelen ayrılma noktası Reynolds sayısının artmasıyla borunun mansabına doğru taşındığı yorumuna ulaşılmıştır. Eğik silindirin açısının artışıyla zamansal ortalama hızın düşey bileşeni artış göstermektedir. Dik silindir eğik silindirle karşılaştırdığı zaman daha fazla türbülans kinetik enerjisi üretir. Akışkanar mekaniğın bir temel prensibi gereğince daha hidrodinamik bir yapıya sahip olan cisim akıma maruz kaldığında daha az türbülans kinetik enerjisi üretir. Başka bir deyimle silindir akıma doğru eğildikçe akım daha hidrodinamik bir forma sahip cisim üzerinden geçiyor ve aynı zamanda akımın boru üzerinde kattetiğı mesafe artmasıyla beraber silindir etrafında ayrılma noktasının ileriye taşınmasına sebep olur ve bunların neticesi olarak eğik silindirin daha az türbülans ürettiğı görölmüştür. Eğik silindirin arkasında oluşan yapıyı daha iyi incelemek amacıyla derinlik boyunca üç farklı bölgeye ayrılmıştır, yüzeye yakın bölge, orta bölge ve tabana yakın bölge, bu üç bölgede farklı nedenlerle oluşan yapılar bu ayrıma sebep olmuştur. Yüzeye yakın kısımda ters gradyan sonucunda meydana gelen çevrintiler ve tabana yakın kısımda atnalı çevrintileri orta kısma transfer olmalarıyla beraber bu bölgede fazla türbülans yaratmasına neden oluyorlar. En az alınan hız ölçüm noktalarına kadar akım doğrultusundaki türbülans çalkantı bileşeni silindirden mansaba doğru uzaklaşarak halen yaşamaya devam etmekte ve azalması görünmemektedir. Diğer türbülans çalkantı bileşenler için bu geçerli değıl ve bu bileşenler bi yerden sonra sönümlleme drumuna

geiyorlar. Ayrıca trblans kinetik enerji retiminde akım doėrultusundakı trblans bileşeni diėer bileşenlerden daha nemli bir etkindir.

1. INTRODUCTION

Flow around and wake behind a rigid body exposed to flow is an important topic of fluid mechanics from the aspects of many different disciplines; hydraulics, coastal/offshore engineering, oceanography, aeronautics, naval architecture, meteorology, geomorphology to name a few. This subject has received particular attention from the coastal engineering and marine/offshore technology related disciplines for, at least, the last fifty years, given the rapid development in the offshore industry such as oil/gas platforms, pipelines, sea outfalls, offshore wind turbines, wave/current energy converters and other marine renewable.

On the other hand, the awareness within the coastal sciences community against the irreversible environmental impacts of “hard coastal protection structures” has convinced many of the practitioners to seek for alternative “soft coastal protection structures” which provides environmental-friendly solutions. In principle, these structures are permeable and compliant rather than impervious and rigid. Pile-supported structures are a good example of this approach. Furthermore, natural structures such as “coastal and estuarine vegetation” were also proven to help the preserve of coastal zones against extreme events as well as human activities.

The substantiated research outputs on the topic of flow-cylinder interaction provides a valuable spectrum of tools for the treatment of aforementioned problems, ranging from simple analytical/empirical design charts to sophisticated numerical models. Research has been performed on the interaction of a single cylinder and cylinder arrays under steady current and waves, including but not limited to the effect of cylinder surface roughness, wall proximity/pipelines, bottom-mounted piles, effect of cylinder array configuration, scour around cylindrical structures. All of these studies started with a circular cylinder aligned perpendicular/upright to the flow direction, but some were extended to non-circular cross-sections or to more complex configurations exposed to flow.

Indeed, the circular upright cylinder is a special case as far as the coastal/offshore structures are concerned. For instance, a tripod wind turbine foundation comprises three inclined cylinders connected by constructive beams, which would undoubtedly alter the flow and scour pattern compared to vertical cylinder case (Stahlmann, 2013, 2014). A pile-supported breakwater would presumably have inclined piles for better stability and reduction in the wave loads, which do not behave identical with vertical cylinders (Yagci et al, 2006).

If the cylinder is not perpendicular to the flow direction; the generated wake region, secondary flow structures and the loads on the cylinder change considerably. With this motivation, the present study aims at getting a better understanding of flow around and wake behind a cylinder mounted on the bed and inclined towards downstream.

1.1 Objective and Scope of the Study

The purpose of this study is understanding the interaction of an inclined pile type of cylinder mounted on the bed with the flow, focusing on the effect of cylinder inclination on the mean and turbulent characteristics of the flow with reference to the vertical cylinder case. Some of the important questions that are envisaged to be answered by this experimental campaign are listed below:

- How does the general secondary flow pattern around the cylinder (horseshoe vortex, lee-wake vortices, downflow, etc.) change with the inclination of cylinder axis?
- To what extent is the “separation distance” at the upstream of the cylinder near the bed affected with the inclination? Does the separation distance decrease, increase or remain the same?
- How is the “vortex shedding” mechanism behind the cylinder affected with the inclination? Is it suppressed or is it reinforced as the inclination increases? Does the vortex shedding frequency (i.e. Strohal number) change?
- Does the turbulence production increases or decreases with the inclination? Which component of the fluctuation velocity is affected most?

- How does the mean flow change with the inclination? Does the resistance of the cylinder increase with the inclination, or does it become a more “hydrodynamic” form as the inclination increases?
- How does the flow recover at the downstream of the inclined cylinder? Does the recovery happen earlier or later than the upright cylinder case?
- How does the reconciliation between the near-bed horseshoe vortex (convected downstream) and lee-wake vortices shedding behind the cylinder happen for the inclined cylinder case?

The answers to all of the above questions have very important implications from marine structures as well as general hydraulic structures and aquatic vegetation are concerned.

1.2 Scope and Method of The Study

To achieve the above answers, an experimental study was conducted in a flume located in the Hydraulics Laboratory of Istanbul Technical University. Although the scope of this study is limited with the steady flow case only, the end-products would presumably give an introductory insight of what is expected to happen in the marine environment. The interpretation in the results and conclusion sections reveal the accuracy of this statement.

In the experimental study, an emergent cylinder, one end of which was mounted on the flume bed, was tested under two different flow rates and five different inclination angles, one of which is the upright case for reference. The inclination of the cylinder axis was maintained towards the downstream at 0, 15, 30, 40 and 50 degrees with the vertical. The two flow rates, 17 and 47 l/s correspond to $Re = 1.08 \times 10^4$ and $Re = 2.82 \times 10^4$ in terms of cylinder Reynolds number.

The three spatial components of the velocity time series were measured at the downstream of the cylinder as well as at the undisturbed flow region. For the inclined cylinder cases, velocity measurements at the immediate upstream of the cylinder were also performed. These measurements were conducted by means of a “third generation acoustic Doppler velocimeter (Vectrino II)” at the vertical plane, which coincides with the centerline of the channel (and cylinder) cross-section.

In addition to the velocity measurements, flow visualization was performed at the near-bed region immediate upstream of the cylinder. A “Dantec Ray Power 2000mW laser sheet” was used for the flow visualization which was shot upwards beneath the bottom of the flume bed through the specially manufactured transparent section. The plane of the laser sheet was again the vertical plane that coincides with the centerline of the flume cross-section and a camera took video recordings from the glass sidewall of the flume. With the help of this flow visualization exercise, the extent of the separation region near the bed was determined.

2. LITARATURE REVIEW

2.1 Open Channel Flow

The hydraulics of open channel flow is particular interest are of civil engineering since this type of flow is ubiquitous in nature (e.g. rivers, and natural streams) as well as human-made channels, as well as navitaion and irrigation canals, drainage ditches, sever and culvert pipes. In open channel flow, an additional resistance is created due to obstacles when flow exposed to rigid or flexible elements. In this subsection, though it is well-known facts by civil engineers, some fundamental descriptions about the open channel hydraulics are given in order to create better background for the discussion of the obtained results

Open-channel flow involves the flow of a liquid in a channel, which exists a free surface between the flowing fluid and fluid above it (mostly the atmosphere). In an open channel flow the principal forces at work are inertia, gravity and viscosity. However, the original motion is the fluid weight gravity obliges the flow to downhill. Under steady, fully developed flow conditions, the component of the weight force in the direction of flow is balanced by the equal and opposite shear force between the fluid and the channel surfaces.

Open channel flow are most important because the natural drainage of water through the stream, rivers and estuarine, delta systems is a complex model of open channel flow. Clearly the character, description, and complexity of open-channel flow geometry are quite variable and there are many ways to classify a flow in a developing, fully developed, and according to Reynolds number to laminar or turbulent conditions but the above mention are valid for pipe flow and open channel flow. Some of the classification of the flow are own of the open channel flow that describe briefly below.

A manner of the flow at the open channel is steady if the derivatives of velocity to the time is zero ($\partial u / \partial t = 0$), that means velocity of flow doesn't change by the respect of the time and it is unsteady when $\partial u / \partial t \neq 0$.

The other classified of the open channel flow is as uniform, non-uniform .If the depth of the flow does not differ along the channel ($(dy)/(dx=0)$) the flow known as an

uniform flow. Conversely it is non-uniform flow if the depth varies with distance ($dy/dx \neq 0$) (Munson et al, 2002).

The velocity is actually zero at the wetted boundary of the channel, and increases to a maximum at the center of the channel and a little distance beneath the surface. The region near the wetted boundary is called the boundary layer, and most of the change in velocity takes place across it. This means that the quantity V is close to the velocity of most of the water, and we use it as if this were true. The approximate independence of our results on the actual velocity distribution is a consequence of the thickness of the boundary layer. According to the earlier study at the narrow flume with $Ar=b/h < 5$ where Ar was the ratio of the free surface width b on the water level h a secondary flow in the cross section of the channel transports low momentum fluid from the lateral walls to the central section of the channel. The maximum velocities due to this motion in the cross section of the channel take place beneath the free surface (Stearns, 1883).

2.2 Immersed Bodies

Flow over a rigid body has been one of the most important topics in the fluid dynamics for over decades. The character of the flow field depends on the shape of the object. For an each shaped object, the flow pattern and related forces depend strongly on various parameters such as size, orientation, speed and fluid properties. By the concepts of dimensional analysis, the important dimensionless parameters are the Reynolds Number (ratio of inertia forces and viscous forces), sometimes the Froude Number (ratio of inertia forces and gravity forces).

At generally when a circular cylinder is immersed on a bed, the flow wills mainly changes. As seen in the Fig (2.1) downflow will appear by the decline of velocity in front of cylinder and horseshoe vortex will formed at the upstream. The streamline will get constricted and lee wake vortices will created at the downstream (Sumer and Fredsoe, 2006).

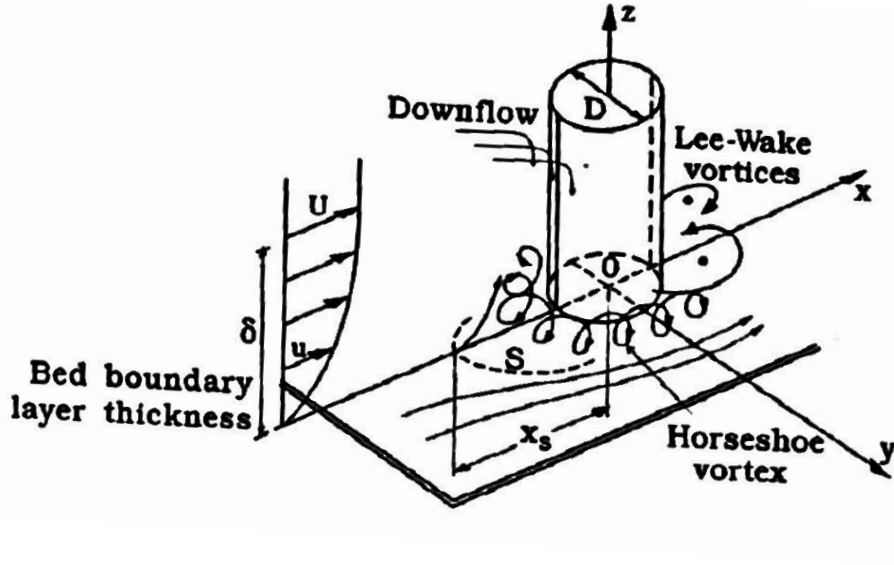


Figure 2.1: The sketch of three dimensional flow around circular cylinder (Sumer and Fredsoe, 2006).

The flow pattern over a cylinder strongly depends to Re number and different flow regime that appeared by variation of Re value. The Re is a non-dimensional quantity that describes the character of flow.

$$Re_D = \frac{DU}{\nu} \quad (2.1)$$

In which D is the diameter of the cylinder, U is the flow velocity, and ν is the kinematic viscosity.

The flow around the cylinder categorized to wake region and boundary layer part. The wake region is big as enough to compare to D diameter of cylinder but the thickness of the boundary layer is so small which not comparable with cylinder diameter Fig (2.2) (Schlichting, 1979).

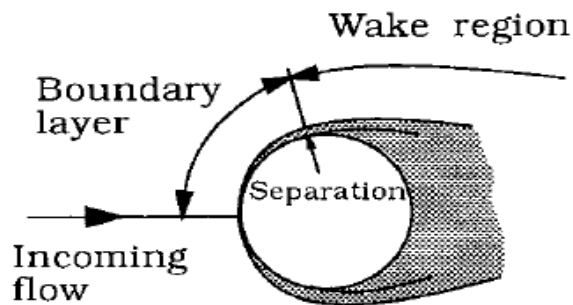


Figure 2.2 : Scheme of boundary layer and wake region over a circular cylinder (Sumer and Fredsoe, 2006).

At the value $Re < 5$ there is no considerably separation but when the Re number is about 40 the wake region becomes unstable and this leads to birthing a new event that called vortex shedding.

For the $Re > 300$ the wake region is completely turbulent however the boundary layer around the surface of cylinder is laminar yet. When the $Re = 400$ the settled vortices are turbulent.

In the range of $3 \times 10^5 < Re < 3.5 \times 10^5$ that called the critical flow regime transition to turbulent in the boundary layer occurs just at one part of cylinder. Boundary layer of both side of the cylinder transition to turbulence in the supercritical regime where $3.5 \times 10^5 < Re < 1.5 \times 10^6$ and finally by increasing Re number to $Re > 4.5 \times 10^6$ turbulently boundary layer occurs over the cylinder surface in everywhere (Sumer and Fredsøe, 2002). Figure. (2.3) was shown formation and transformation of the vortices

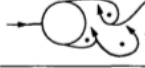
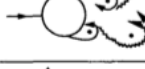
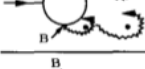
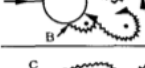
	No separation. Creeping flow	$Re < 5$
	A fixed pair of symmetric vortices	$5 < Re < 40$
	Laminar vortex street	$40 < Re < 200$
	Transition to turbulence in the wake	$200 < Re < 300$
	Wake completely turbulent. A: Laminar boundary layer separation	$300 < Re < 3 \times 10^5$ Subcritical
	A: Laminar boundary layer separation B: Turbulent boundary layer separation: but boundary layer laminar	$3 \times 10^5 < Re < 3.5 \times 10^5$ Critical (Lower transition)
	B: Turbulent boundary layer separation: the boundary layer partly laminar partly turbulent	$3.5 \times 10^5 < Re < 1.5 \times 10^6$ Supercritical
	C: Boundary layer com- pletely turbulent at one side	$1.5 \times 10^6 < Re < 4 \times 10^6$ Upper transition
	C: Boundary layer comple- tely turbulent at two sides	$4 \times 10^6 < Re$ Transcritical

Figure 2.3 : Regimes of flow around cylinder in steady current (Sumer and Fredsøe, 2006).

by increasing the Reynolds number.

At very low Re_D , during the so-called creeping flow, inertia forces are assumed to be negligible; hence, the governing equations for the flow (Navier-Stokes equations and the continuity equation) are greatly simplified. Stokes succeeded in obtaining a solution for these equations and the drag force can be calculated by Eq. (2.2)

$$F_D = 6\pi\mu \frac{D}{2} U_0 \quad (2.2)$$

Where D is the radius of the cylinder, U_0 the freestream velocity and μ the dynamic viscosity of the fluid. This relationship may be used up to $Re_D = 0.5$ with negligible error. This flow range is often called the Stokes flow. The drag coefficient is defined as Eq. (2.3)

$$C_D = \frac{F_D}{\rho \frac{U_0^2}{2} A} \quad (2.3)$$

Where A is the projected area (equal to πR^2), which can be expressed as Eq. (2.3)

$$C_D = \frac{24}{Re_D} \quad (2.4)$$

where Re_D is calculated by Eq. (2.4)

$$Re_D = \frac{U D}{\mu/\rho} \quad (2.5)$$

Eq. (2.2) is known as Stokes' law. Sometimes Eq. (2.4) is also referred to as Stokes' Law. An extension of Eq. (2.4) has been formulated using a method of successive approximations to the governing equations (still at low Re_D). This formula reads

$$C_D = \frac{24}{Re_D} \left[1 + \frac{3}{16} Re_D \right] \quad (2.6)$$

Equation (2.6) may be used up to $Re_D \approx 100$. At higher values of Re_D , it is necessary to rely on empirical expressions based on experiments.

When applied to particle mechanics, the following regimes are introduced:

$$Re_D \leq 0.2 \text{ Stokes flow } C_D = \frac{24}{Re_D} \quad (2.7)$$

$$0.2 < Re_D < 500 \text{ Allen flow } C_D = \frac{18.5}{Re_D^{0.6}} \quad (2.8)$$

$$500 < Re_D < 10^5 \text{ Newtonflow } C_D = 0.44 \quad (2.9)$$

2.2.1 Force on oblique circular cylinder

Flow pattern over an inclined cylinder may be different from the upright case and the force on the body may change considerably (Fig. (2.4)). It has been proved in most cases the independence principle is applicable at the subcritical Reynolds range Schlichting (1979), also by the studies of Norton et al. (1981), this principle is valid for postcritical flow. At the transcritical value of Reynolds number, where the shape of vortex shedding and drag changes this independence principle is not valid (Bursnall and Loftin, 1951).

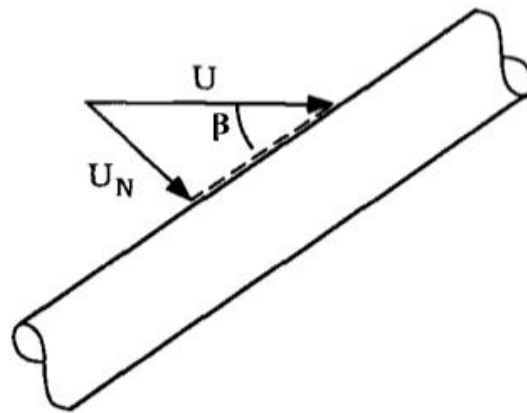


Figure 2.4 : The distribution of force along the oblique cylinder (Sumer and Fredsoe, 2006).

The investigation of Kozakiewicz et al. (1995), shows that for the angle of attack $45^\circ \leq \beta \leq 90^\circ$ the force coefficients are independent of β and by increasing the inclination angle the lift force power spectrum became broader.

At the inclined condition the streamlines of incoming flow near the cylinder are curved likewise that the flow past the cylinder is nearly normal to the cylinder (Figure (2.5)). This may be attributed to the remaining of the wake pressure over the length of the cylinder.

By the findings of flow visualization the streamlines do not bend for the smaller angle of attack than 35° and drag coefficients are not independent of β .

Yagci et al. (2006) investigated pressure distribution over an oblique circular cylinder as a pile of breakwater (Figure (2.6)). By their findings the uppermost value of dynamic

wave pressure may not occurred at the section perpendicular to the wave direction. It that means the so extremely small surface may rotate and make an angle with the incoming wave path and the maximum dynamic wave pressure around the cylinder is near to a location making an angle of 22.5° with the wave direction.

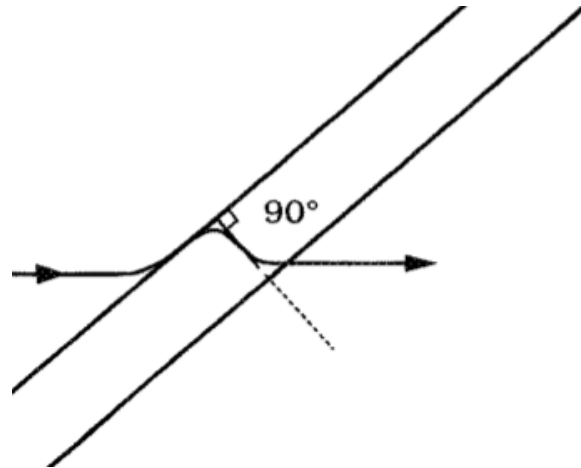


Figure 2.5: The incoming flow at the angle of attack passed along the cylinder by 90° (Kozakiewicz et al, 1995)

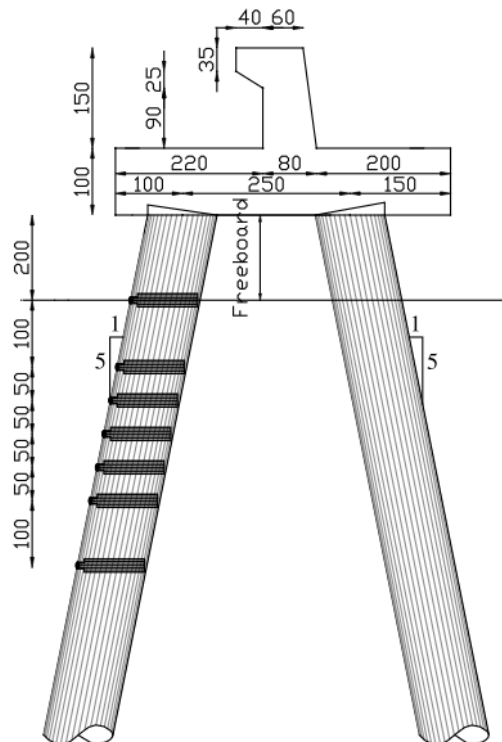


Figure 2.6 : The pressure distribution over a pile of breakwater (Yagci et al, 2006).

By the increasing of depth in line dynamic wave pressure became more significant. Base to the water particle measurements streamwise velocity u has more important role than vertical velocity by the presence of the piled breakwater. A lateral momentum transfer which means minor energy dissipation was happened at the land ward of the breakwater.

2.3 Boundary Layer and Separation of Flow

Boundary layer is thin region on the surface of a body and due to velocity gradient the viscous effect is different within or out side of viscosity that caused to shear stress has a deferring effect upon the flow. By the increasing the Reynolds number the thickness of boundary layer subsequently increase Fig (2.7).

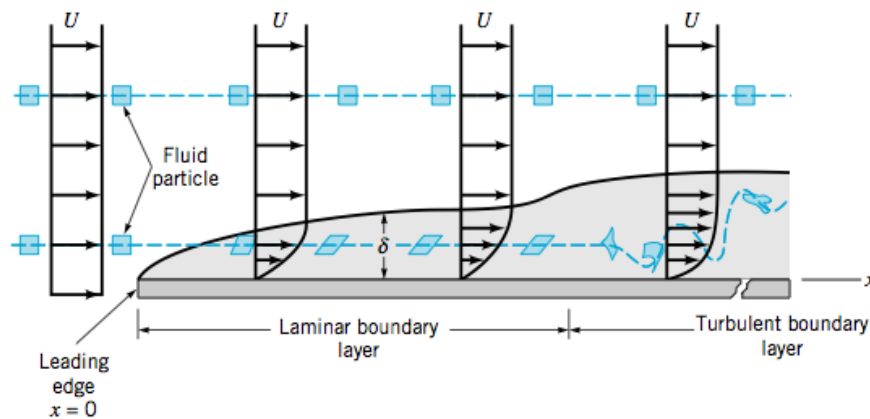


Figure 2.7 : The develop of boundary layer and transition from laminar to turbulent (Munson et al, 2002).

A negative pressure gradient is termed a favorable pressure gradient will counteract the retarding effect of the shear stress in the boundary layer and positive pressure gradient has the opposite effect and is termed the adverse pressure gradient. By the effect of adverse pressure gradient separation created at the flow. As indicated in the Fig. (2.8) the velocity near the surface reduces gradually and this retardation of flow brings the wall shear stress at the point S on the wall to zero. The shear stress becomes negative and the flow reverses and a region of recirculating flow develops

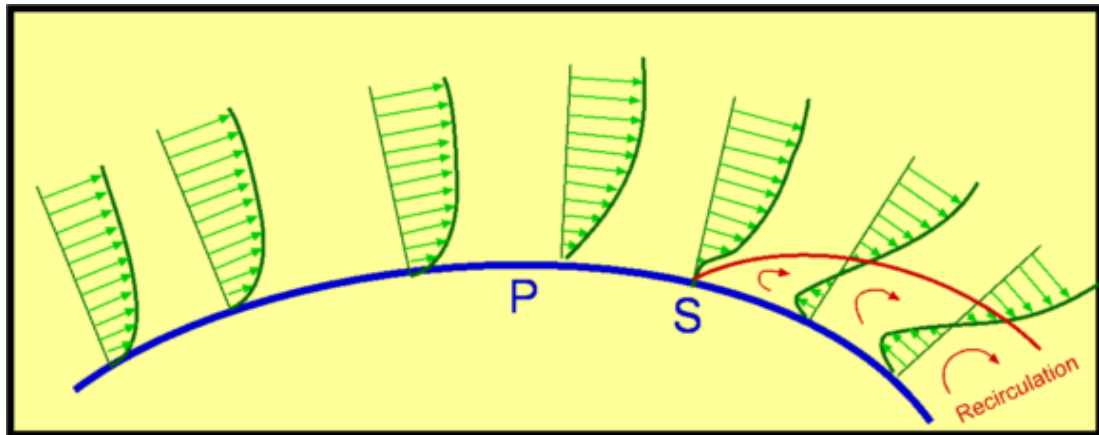


Figure 2.8 : The generating of boundary layer over a surface (Url-1).

from this point forwards. As seen in the Figure the flow no longer follow the body and the flow have separated. At the point S where the shear stress is zero is called the point of separation.

At low Re_D , the separation point is located at the rear stagnation point and with increasing Re_D moves forward and reaches $\theta \approx 80^\circ$ from the front stagnation point at approximately $Re_D=1000$. Pressure drag begins to dominate and the Drag Coefficient becomes almost independent of the Reynolds number until about $Re_D = 5 \times 10^5$, when the transition from Laminar to Turbulent Flow occurs before separation. As a result, the point of separation moves to the rear, making the wake smaller and abruptly reducing drag coefficient. At large Reynolds number, flow over the front half of a cylinder may be divided into a thin Boundary Layer region where viscous forces are dominant, and an outer region, where the flow corresponds to that of an inviscid fluid.

By the effect of viscous, particle in the boundary layer has no energy. It that means the particle in the boundary layer does not have sufficient energy to pass over from C to F. This defect of kinetic energy is shown in Fig (2.9) in the velocity profile. At the point D where separation over the cylinder was occurred the velocity gradient at the wall and wall shear stress are zero. Due to separation of boundary layer the average pressure gradient on the rear of the cylinder is less than on the front half (Munson et al, 2002).

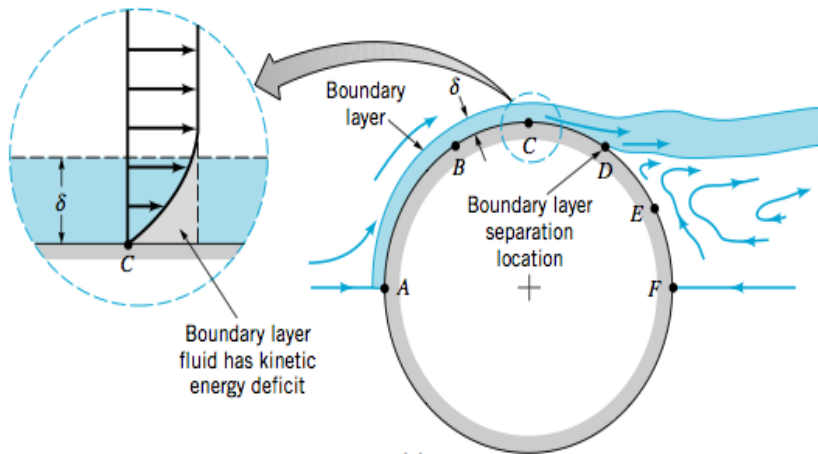


Figure 2.9 : boundary layer over a cylinder (Munson et al, 2002).

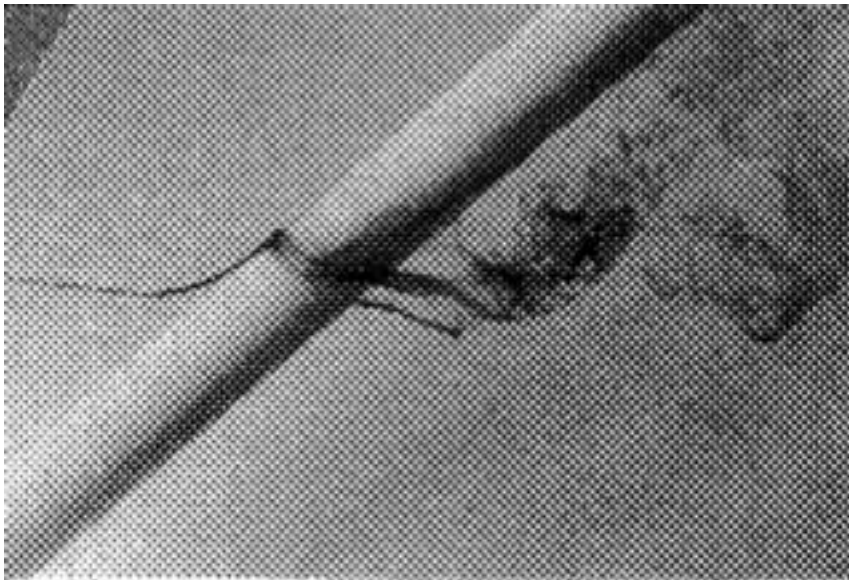


Figure 2.10 : Visualization of the separation of boundary layer over a circular cylinder at the wake region (Kozakiewicz et al, 1995).

2.4 Vortex Shedding

Vortex shedding is a periodic phenomenon that happened when the current flow of a fluid is interrupted by an obstacle structure. Vortex shedding befallen at $Re > 40$ in laminar regimes. At this Reynolds value boundary layer around the body generated by the adverse pressure gradient at the behind of structure (Sumer and Fredsoe, 2006).

As shown in Fig (2.1) two types of vortex are appeared around the cylinder, horseshoe vortex and lee wake vortex (Sumer and Fredsoe, 2006).

These vortices occurred and developed at the region near of the cylinder. At this region the value of the pressure fluctuations and turbulent kinetic energy were much larger than the boundary layer turbulence over the cylinder (Simpson, 2001).

For generation of the horseshoe vortex the adverse pressure gradient that produce by the presence of cylinder must be adequately strong that the boundary layer on the bed can separate. This separated boundary layer subsequently rolls up to generate a spiral vortex around the cylinder, which developed to downstream.

The lee wakes vortices shaped by the rotation in the boundary layer over the surface of the cylinder. The shear layer that created by side edge of cylinder rolls up to generate these vortices in the lee side of the cylinder.

2.4.1 The mechanism of vortex shedding

The boundary layer at the upstream of the cylinder must dominate over a strong pressure gradient that established by the cylinder. Leads to this process a separation created at the flow. In this separation region vortex system is extended around the cylinder (Dargahi, 1990).

The primary vortex that appeared at the both sides of cylinder at the laminar flow regime were unstable which is shown with A and B at Fig. (2.11). The direction of Vortex A was clockwise and the other one was counterclockwise. The bigger vortex (A) has more enough energy to pushed the smaller one (B) to the wake region. After shedding the larger one a new vortex (C) will be generated at the same side of cylinder. At this time vortex B has the same condition of vortex A to the vortex C.

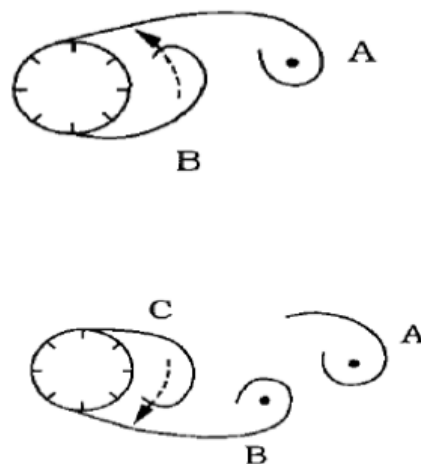


Figure 2.11 : The sketch of creating and shedding of vortex (Sumer and Fredsoe, Hydrodynamics Around Cylindrical Structures, 2006).

This process will go on between the sides of the cylinder (Gerrard, 1966).

2.4.2 Strouhal number

The Strouhal number is frequency of vortex shedding, that normalized with the velocity of flow U and cylinder diameter D . The vortex-shedding frequency, when normalized with the flow velocity U and the cylinder diameter D , can on dimensional grounds be seen to be a function of the Reynolds number:

$$St = St(Re) \quad (2.10)$$

In which

$$St = \frac{f_v D}{U} \quad (2.11)$$

And f_v is the vortex-shedding frequency. Fig. (2.12) shows the variation of Strouhal number according to Re

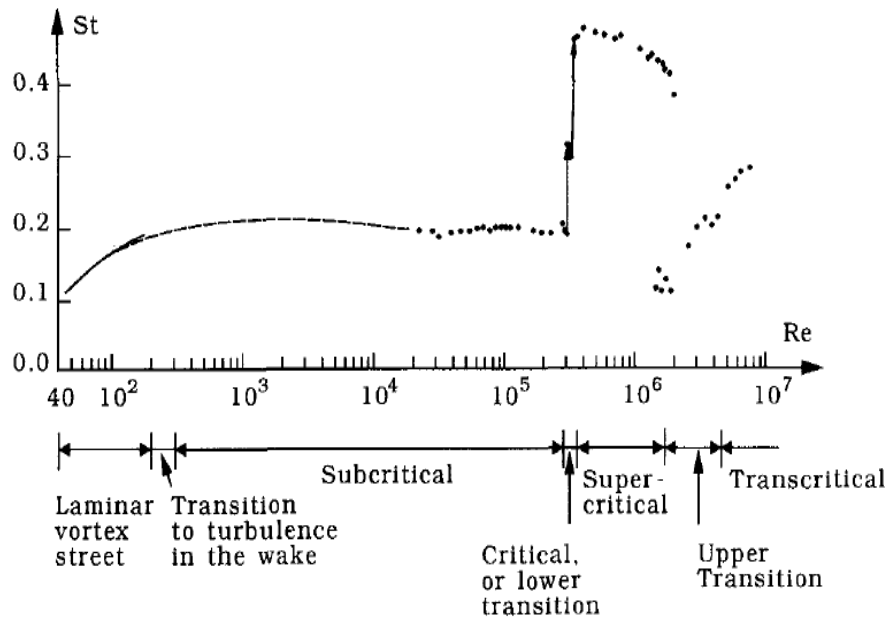


Figure 2.12 : Strouhal number for a smooth circular cylinder (Sumer and Fredsoe, 2006).

As it was discussed at previous chapter and is shown at Fig. (2.12). The vortex appeared at $Re = 40$. At this Reynolds number the Strouhal number is about 0.1 and increases gradually until 0.2 at the Re value 300. In the subcritical regime also the Re value increased significantly, the Strouhal number stood approximately at the same

range. But the number abruptly changed and increased to 0.45 at $Re = 3 - 3.5 \times 10^5$ (super critical flow regime). At the supercritical regime separation points moves to downstream by turbulent boundary layer of separation point of both sides of cylinder Fig (2.13). Due to this moving the vortices interact with a faster rate than in the subcritical regime and leads to larger Strouhal number. The value of Strouhal number reduces to 0.1 when Re number increased to 1.5×10^6 at this Re value the turbulent boundary layer of one part of the cylinder has formed completely but the other side followed transit from laminar to turbulent with respect to time and due to the this asymmetry, lee wake vortices set disorderly. The Strouhal number was recovered again by increasing Re value (Sumer and Fredsoe, 2006).

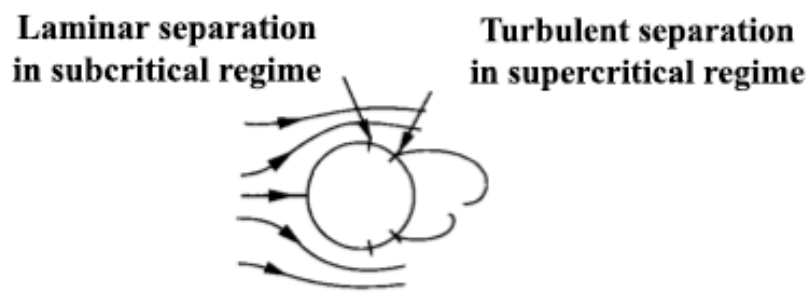


Figure 2.13 : Sketch showing positions of separation points at different separation regimes (Sumer and Fredsoe, 2006).

2.4.3 Scour

Scour is one of the most important processes at the hydrodynamics of marine structure, which is observed at pile of bridges, legs of multi proposal of offshore platform and breakwater piles. Figure. (2.14) shows a foundation of bridge which undergoes erosion by scour process.

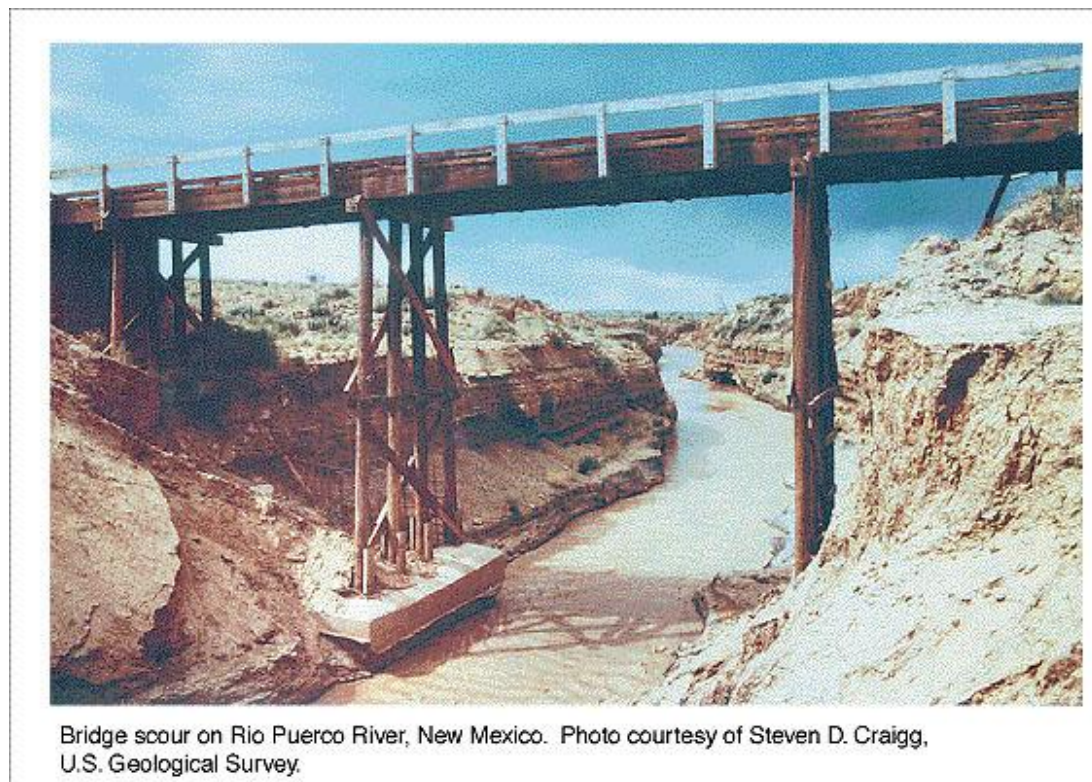


Figure 2.14 : Scour phenomenon is one the main reason of bridge failure (Url-2).

The phenomena of scour around a circular cylinder is set to a three dimensional separation of the flow at the upstream of cylinder and the presence of organized coherent structure of periodical vortex shedding at the base of cylinder. By the studies of Dargahi (1990) and Ettema et al. (2006) the scour process in the downstream is strongly related to the shedding of lee wake vortices.

The most important factor that due to scour processing is horseshoe vortex when matched with the effect of the shrinkage of streamline at the side edges of cylinder. But at the increasing Re number different vortices were observed, which have a periodical manner (Roper, 1967).

Vortices process at the scour hole consists several vortexes as main and secondary vortexes. Figure (2.15) shows that the dominant structure of the vortices corresponding to HV1 at the upstream part of the cylinder also with a small but coherent junction vortices (JV) at the base of cylinder. The forming of boundary layer on the upstream of the cylinder was the main cause of these junction vortices. A comparably constant vortexes as HV2 is detected far from the cylinder. The structure of HV2 is more variability than the HV1 vortexes and missed its coherent

structure before setting again. Finally a secondary bottom attached vortices (BAV) is present only upstream of HV1.

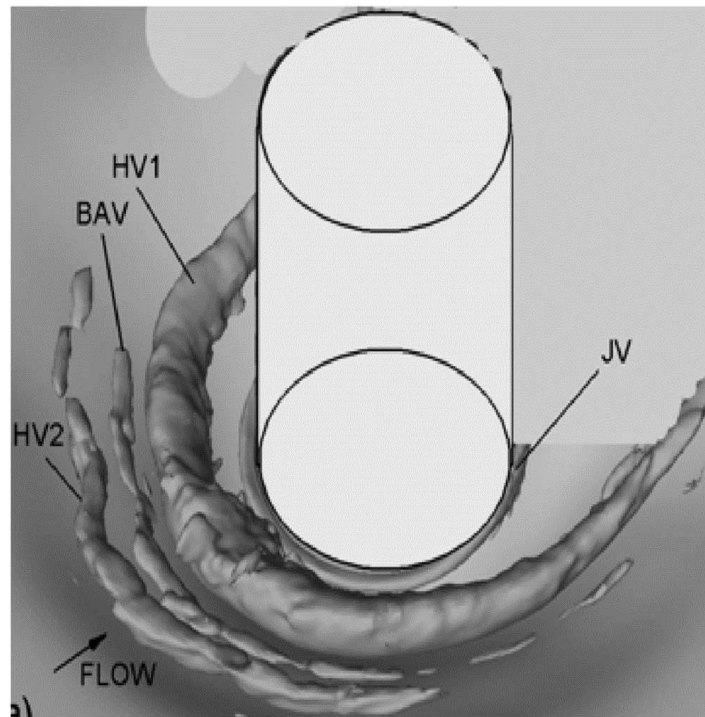


Figure 2.15 : Visualization of the main and secondary vortices inside the scour hole (Kirkil et al, 2008).

The direction of the wake vortices was vertical and their manner look like a vacuum cleaner to intake and suspended the bed material into the main flow field. The wake vortices behind the pier cause strong circulation all over the flow depth forming a wake region behind the pier. Due to the wake vortices that cause strong circulation all over the flow depth forming a wake region behind the pier. The wake vortices are usually recognized from the small scale eddies at the water surface behind the pier that dissipates as they move downstream. The shedding frequency of the wake vortex was to be commensurate proportional to the pier diameter (Salaheldin et al. , 2004).

The development of the vortex system upstream of the cylinder with moveable bed was similar the fixed bed. The other criterion of the scour like thickness of the separated boundary layer, the position of the primary separation point, and the number of vortices continue the same. The instruction of the general flow in the wake of cylinder developed unchanged during scouring; the initial vortices were also shed at the same frequency as for immovable bed. At the low Reynolds number, that viscous flow were prevailed around infinitely long cylinder the aggregation of the vortices that appeared estimate along the line of about 45° (Batchelor, 1967). Base to

Dargahi (1990) studies the streamwise velocity, which close to the cylinder was by four times the initial vortices normal to the flow. Alike phenomenon was expected to at higher Re values.

Three different steps define the mechanism of scour: initiation, primary scouring, and gradual reduction. During the first step switching of the boundary condition from fixed bed to suspended cause no considerable change in the structure of flow around the cylinder. During the primary step the scour profiles were created by the horseshoe vortices. The formation of the horseshoe vortices was inherent in the three-dimensional separated flow field and cannot be prevented by means of collars attached to the cylinder (Dargahi, 1990).

2.4.3.1 Scour depth

The scour depth is directly affected by different subject matter for instance the Shields parameter, the sediment gradation, ratio of boundary layer to cylinder size, the shape factor and the alignment factor

At this case of study was focused to pier diameter more than the other factors because of the rigid bottom during the experiments.

The slope of the scour hole at the upstream and downstream are not symmetric is more or less equal to the angle of internal friction. The slope of scour hole at the upstream was around 32°. The downstream slope of scour hole is almost less steep, but it expands to larger distance s away from the cylinder (Kirkil et al, 2008) Figure (2.16).

The ratio of thickness of boundary layer to the diameter of pier is one the important parameter at scour depth. Due to collected data by Melville and Sutherland (1988) by the increasing δ/D that directly influenced to horseshoe vortex the scour hole increases that means the larger value of δ/D leads to the larger size of the horseshoe vortex Fig (2.17) (Sumer and Fredsøe, 2002).

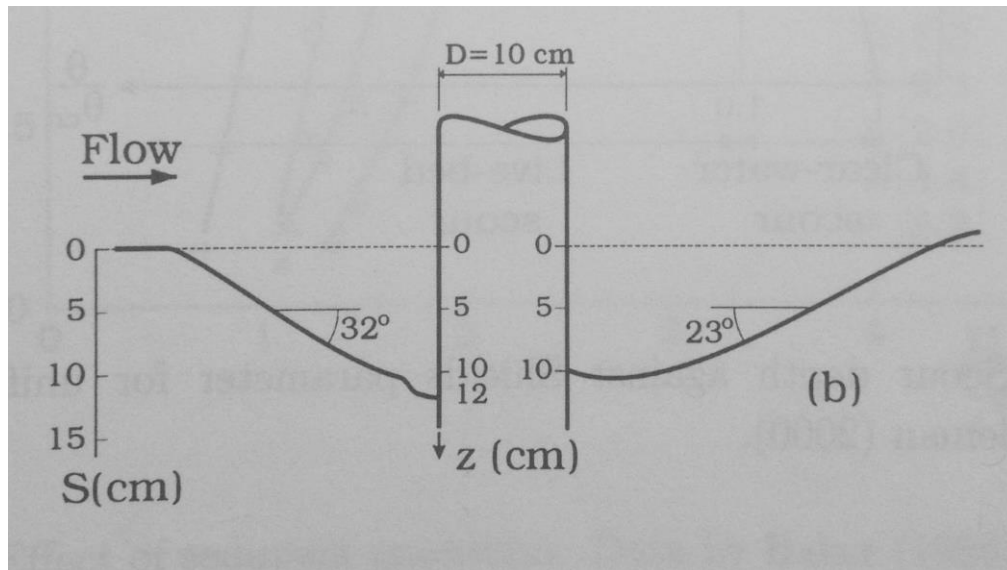


Figure 2.16 : The non symmetric scour hole (Sumer and Fredsoe, 2006).

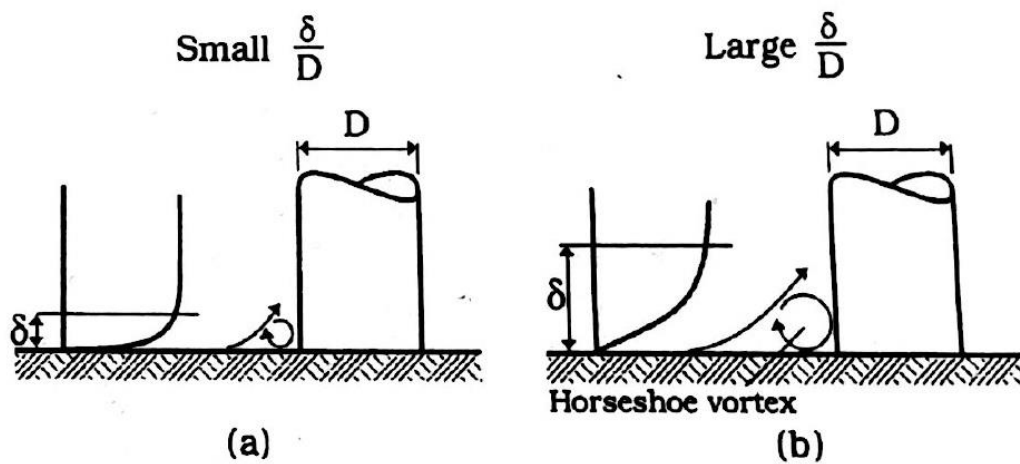


Figure 2.17 : The effect of increasin δ/D to horseshoe vortex (Sumer and Fredsøe, 2002).

3. EXPERIMENTAL SET UP and PROCEDURE

3.1 The Experimental Set Up

The measurements were carried out in the flume at the Hydraulics Laboratory of Istanbul Technical University. The re-circulating flume 18m in length, 0.5m in width, and 0.5m in depth was used throughout the experiments. A view of the flume is given in Fig. (3.1).

The flume has Plexiglass sidewalls and bottom covered with smooth concrete. The bottom part of which cylinder was mounted composed of Plexiglass to facilitate flow visualization. Slope of the flume was 0.002 throughout the experiments.

A pump provided re-circulating flow at the flume. The pump supply water from constant collection tank to head tank located at the upstream of the flume. The water spilled over the V-notch (triangular) weir from this head tank to the flume. The discharge was calculated by the triangular V-Notch weir. To create more smooth inlet water conditions, fluctuation was diminished by tubes located at the upstream of flow.

3.2 Measurement Devices

For the velocity measurements acoustic Doppler velocimeter, Vectrino II (i.e. NORTEK Vectrino profiler, with flexible probe) was utilized. The Vectrino-II is a high-resolution acoustic Doppler velocimeter used to measure turbulence and 3D water velocity in a wide variety of applications from the laboratory to the ocean. The basic measurement technology is coherent Doppler processing, which is characterized by accurate data and no appreciable zero offset (NORTEK, 2000).



Figure 3.1 : The view of re-circulating flume.

The Vectrino-II uses the Doppler effect to measure current velocity. The Doppler effect is the change in pitch that is heard when either the source of a sound or the listener is in motion. When you hear a vehicle with a siren, the pitch is higher when the vehicle is heading towards you, and lowers when it is going away. The change in pitch tells you how fast the vehicle is moving (NORETK, 2000). Sound does not reflect from water, but from particles suspended in the water. These particles are typically suspended sediment or seeding particles, and move with the same average speed as the water. The velocity that is measured is consequently the velocity of the water. The Vectrino-II transmits short pairs of sound pulses, listens to their echoes, and, ultimately, measures the change in pitch or frequency of the returned sound (Nortek, 2000). The Vectrino II provides measurement within the 3 cm height of sampling volume as seen in Fig. (3.2) below. Herein it should be noted that whilst, Fig. (3.2) show the down looking probe, in this study the probe was aligned in the side looking was throughout the experiments.

With the utilization of Vectrino II, the velocity field around the inclined cylinder was measured by Eulerian approach. However, in order to explain the flow patterns that appear at the downstream of the cylinder, it was necessary to visualize the separation of flow that occur at the upstream of the cylinder. In this way, it would be possible to interpret the role of the inclination of the cylinder on the separation of flow at the upstream of the cylinder. In the light of these facts, one laser sheet was utilized for the flow visualization. The laser sheet was composed of two separate parts an operation panel (Ray Power 2000, Dantec) and laser output beam (80X80 light sheet series, Dantec Dynamics A/S). The 80X80 High power Light-sheet series for Dual Power and Ray Power lasers is based on a modular concept allowing the user to adapt the functionality to his experiment. By combining the various modules, the sheet thickness and divergence angle can be adjusted to cover a wide variety of applications. At this experiments Entrance module P 7.4 mm was used 9080X8961. The maximum output power of the beam is more than 2000 mW and wavelength of the laser beam is 532nm. This is a Class 4 laser. This means that intra beam viewing and skin exposure is hazardous, and viewing diffuse reflections may be hazardous. The laser beam may also represent a fire hazard (Dantec, 2000).

During the experiments by laser sheet all of safety qualification was considered and special eyeglasses was used.

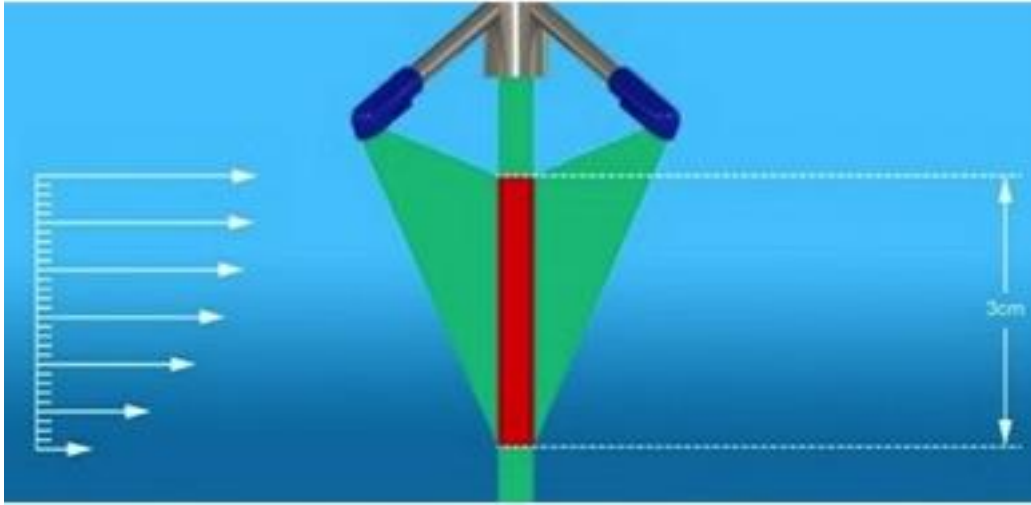


Figure 3.2: Sampling volume of the Vectrino II for downlooking alignment (Nortek, 2012) .

3.3 Procedure

In the experiments, cylinders were mounted at the centerline of the flume, far from the inflow part of the flume to ensure that the incoming flow was fully developed before it reached the cylinder and inclination angle θ , which was varied from 0° to 50° . The θ is the angle between the normal of channel bottom and the cylinder. The mounted view of the inclined cylinder was given in Fig. (3.3). Diameter of cylinder was chosen 7.5 cm throughout the experiments to prevent the contraction effect of cylinder ($D/b < 1/5$). For the forming of vortex sheddings over a cylinder and prevent of the effect of wall proximity on obstacle cylinder the distance of wall and cylinder must be larger than this value $\frac{e}{D} > 0.3$ (Kozakiewicz et al, 1995). This ratio was $\frac{e}{D} = 2.9 > 0.3$ throughout the experiments which e is the gap between the cylinder and the wall. Each inclination angle was tests exposed to 3 different discharges ($Q_1 = 47$ lt/s $>$ $Q_2 = 17$ lt/s $>$ $Q_3 = 7$ lt/s). The discharge was measured by 90° V-notch (triangle) sharp crested weir and calculated by

$$Q = C_{wt} \frac{8}{15} \tan\left(\frac{\alpha}{2}\right) \sqrt{2g} H^{5/2} \quad (3.1)$$

Where

H is the height of the upstream free surface above the crest of the weir α is the angle of the V-notch. Typical values of C_{wt} are in the range of 0.58 to 0.62 (Munson et al, 2002).



Figure 3.3 : Mounted obstacle pier and ADV probe.

During the experiments velocity and turbulence measurements were carried out by ADV (Vectrino II) The ADV was installed to traverser system established at the top of flume so that ADV could move/positioned along X, Y and Z-axes. The probe of ADV was placed in side looking direction as aforementioned above. During the experiments, the probe was stable along all directions. As stated above, the velocimeter probe was oriented in the side looking direction and 18 points with 2 mm spatial interval was detected throughout the velocity measurements as shown in Fig. (3.4). During the experiments 22086 points were measured at the total which of 16416 observed points were belonged to downstream and 5670 of points were related to upstream.

Throughout the experiments 5 inclination angle was examined. For each inclination angle, 3 discharges were applied. In other words, in 15 different experimental setups velocity measurements were undertaken. In Fig. 3.5 the sketch of measurement points for different inclination angles were illustrated.

In all the experiments, water depth was kept constant as 0.25m. All the experiments were started after the water surface level was established entirely. Sampling duration was 90 s and sampling frequency was 100 Hz in the velocity measurements. This

sampling duration (i.e. sampling number) was chosen based on the study of Yagci and Kabdasli (2008) examined the similar flow ranges and observed that velocity records for more than 50 – 60 s leads to a constant value and this means that collecting data for longer than 60 s does not add to data quality. The schedule and conditions of experiments was summarized in Table 3.1.



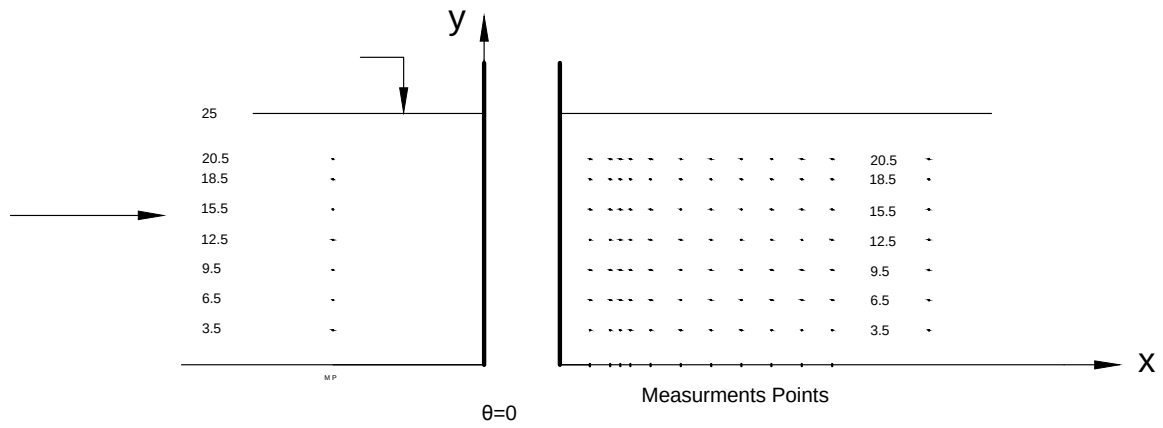
Figure 3.4: The configuration of ADV and probe.

The laser sheet was placed vertically underneath the base of the flow flume. The output beam was oriented in the vertical direction and the beams penetrated the plexiglass bottom during the flow visualization. A general view of the setup for flow visualization is as given in Fig. 3.6. A camera, which is able to take 24 frames per seconds, was placed in the side-looking direction for the flow visualization process. The duration of the recording was 120 s and the power of laser was performed between 3- 4.7 mW.

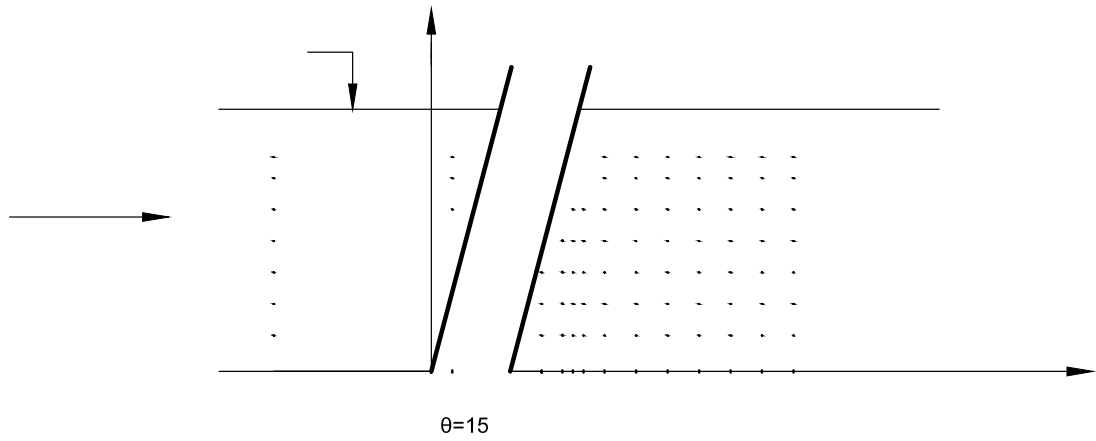
So as to obtain more reliable measurements, preliminary experiments were undertaken to check the following points.

- It was checked that if the time averaged non-disturbed mean velocity profile at the upstream of the cylinder fit to logarithmic velocity profile.
- The influence of shape and alignment of the deployment apparatuses on the flow field was examined to minimize this effect Fig. (3.7).

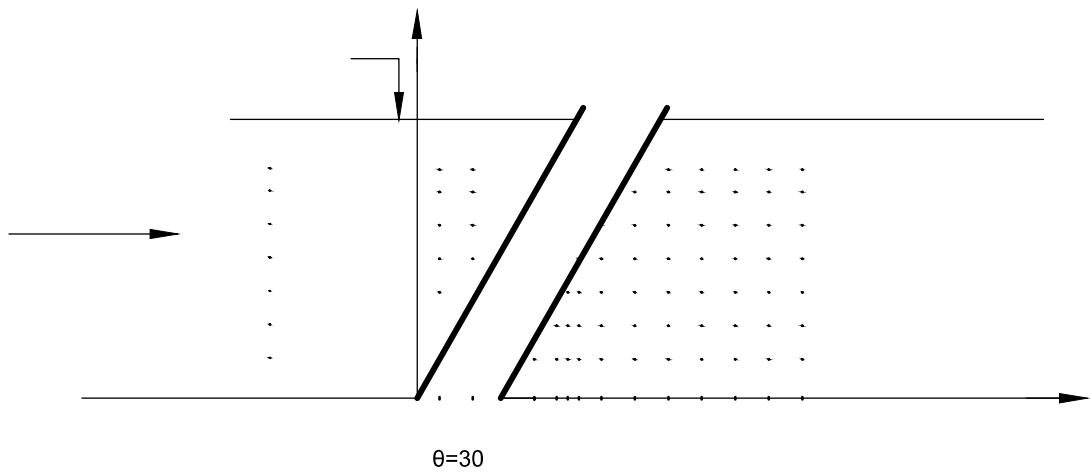
- It was checked that the sluice gate did not disturb the velocity profile in the measurement section Fig.(3.8).



(a)

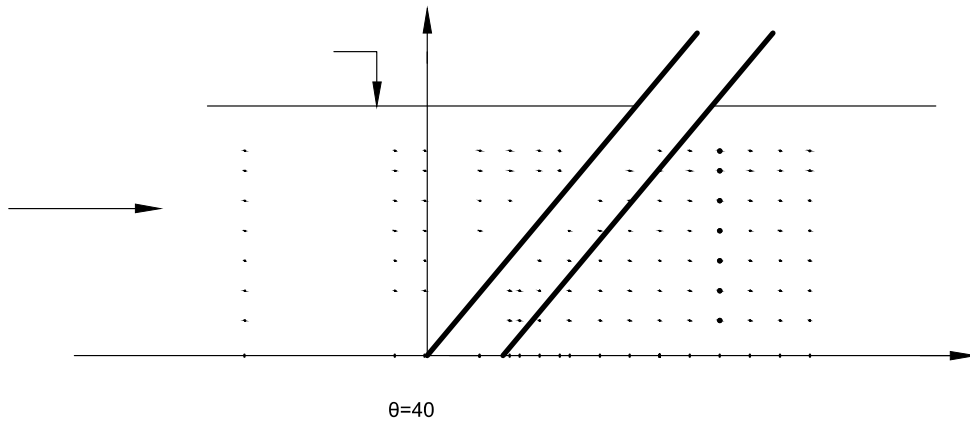


(b)

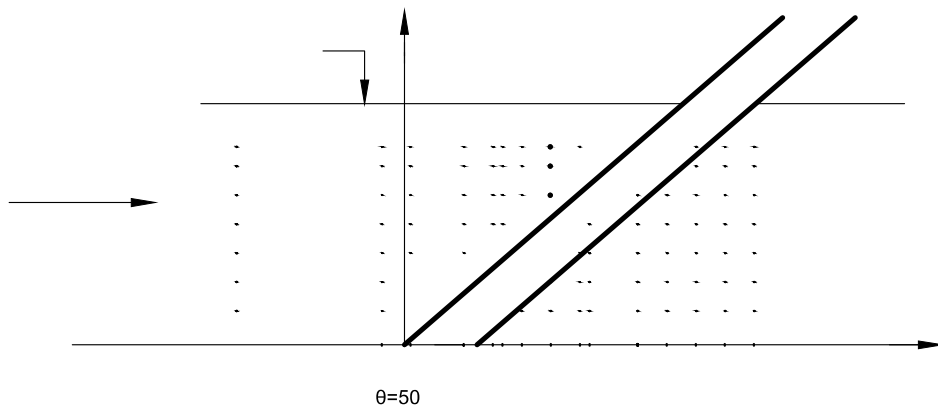


(c)

Figure 3.5 : The sketch of measurement points for different inclination angles a)0° b)15° c)30° d)40° e)50° .



(d)



(e)

Figure 3.5 (continued) : The sketch of measurement points for different inclination angles a) 0° b) 15° c) 30° d) 40° e) 50° .

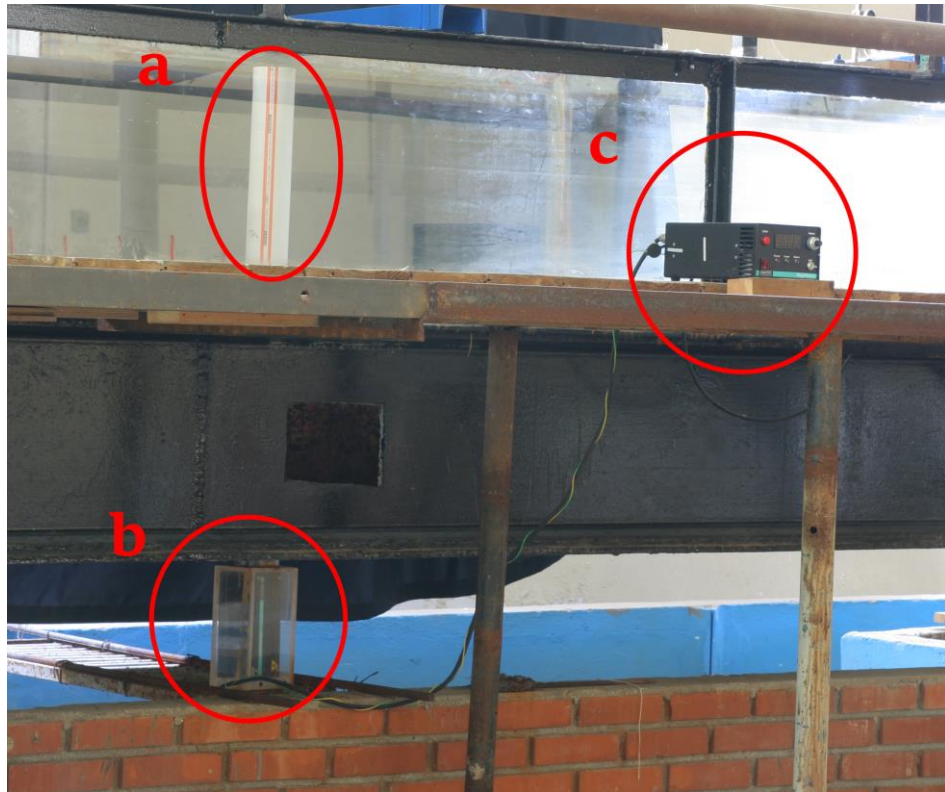


Figure 3.6 : The state of pier (a), laser beam (b), and laser panel (c).

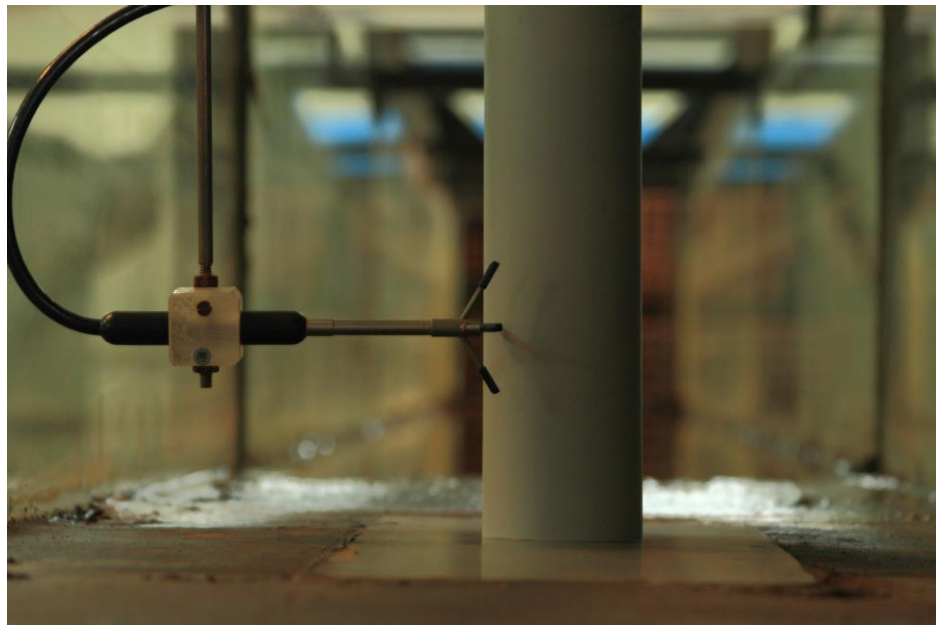


Figure 3.7 : Alignment of the center of the pier with transducer.

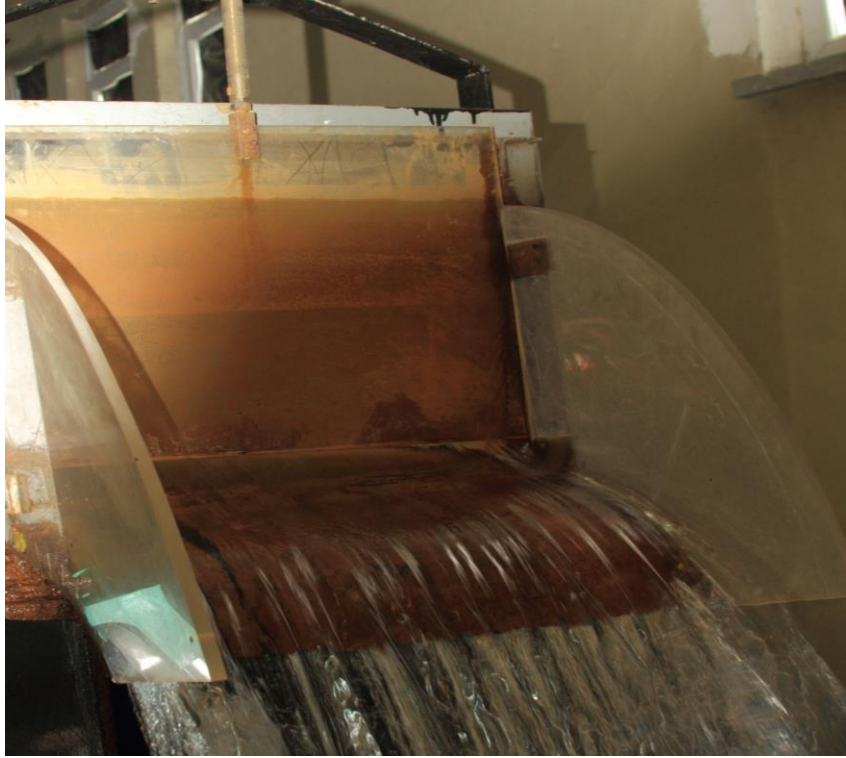


Figure 3.8 : The view of sluice gate.

Table 3-1: Experimental Schedule.

Angle of inclination	Exp. No	Number of Measurement points	Discharge (Lt/s)	Diameter of Cylinder (Cm)	Water Depth (Cm)	Sample of Duration (s)	
0°	Case 1	Downstream	126	7.5	25	90	
		Upstream	1386				
	Case 2	Downstream	126				17
		Upstream	1512				
	Case 3	Downstream	126				7
		Upstream	1386				
15°	Case 4	Downstream	198	7.5	25	90	
		Upstream	1044				
	Case 5	Downstream	180				17
		Upstream	1188				
	Case 6	Downstream	180				47
		Upstream	1188				
30°	Case 7	Downstream	360	7.5	25	90	
		Upstream	1008				
	Case 8	Downstream	396				17
		Upstream	972				
	Case 9	Downstream	396				7
		Upstream	1008				
40°	Case 10	Downstream	522	7.5	25	90	
		Upstream	1152				
	Case 11	Downstream	540				17
		Upstream	1152				
	Case 12	Downstream	540				47
		Upstream	1152				
50°	Case 13	Downstream	720	7.5	25	90	
		Upstream	756				
	Case 14	Downstream	630				17
		Upstream	756				
	Case 15	Downstream	630				7
		Upstream	756				

4. ANALYSIS METHOD

4.1 Despiking of The Data

The velocity measurement device “ADV” has recently become a popular in experimental studies. Some researchers and engineers have commonly used this instrument in both hydraulic experiments and outdoor measurements such as natural estuarine systems, where other measurement techniques such as laser Doppler anemometers are impractical.

The utilization of ADVs is easy and so facile to set up. However, these devices have some disadvantages like others. One of the major problems about the ADV is that the spike noise looks similar to turbulent fluctuations and this may leads to misleading turbulence results. Due to the above reasons, crude ADV data does not provide fully reliable turbulent results and the obtained results should never be used before adequate pre processing (Mori et al , 2007). Despiking process contains two independent stage: detecting the spike and replacing the spike

There are several despiking algorithms have been proposed to remove spike noise from recorded ADV data set, for example RC filters method, Tukey 53H Method, Acceleration thresholding method or wavelet thresholding method. At this presented study, the crude data despiked with a software code that modified by Nobouhito Mori (2005) and used 3D phase-space method, which created by Goring and Nikora (2002) and modified by (Wahl, 2003). Despiking is a complicated processes and it may damage correct dates during eliminating the spikes. From the preceding findings Goring and Nikora (2002) were carried out and test all above methods to determine which method has best passes a clean data set but will refine contaminated data. The results show that the phase space method works extremely well for numerous ADV data sequences

At this method that uses the concept of a 3D Poincare map in which the variable of u and its first and second derivate, Δu and $\Delta^2 u$ are plotted against each other. The good data are enclosed within an ellipsoid in the Poincare map and the points that lied out

the ellipsoid are defined as spike. The method iterates until the number of detected spikes becomes zero (Mori et al, 2007). At the Figure.(4.1) shown the spike data which was recognized by red circle out of the ellipsoid

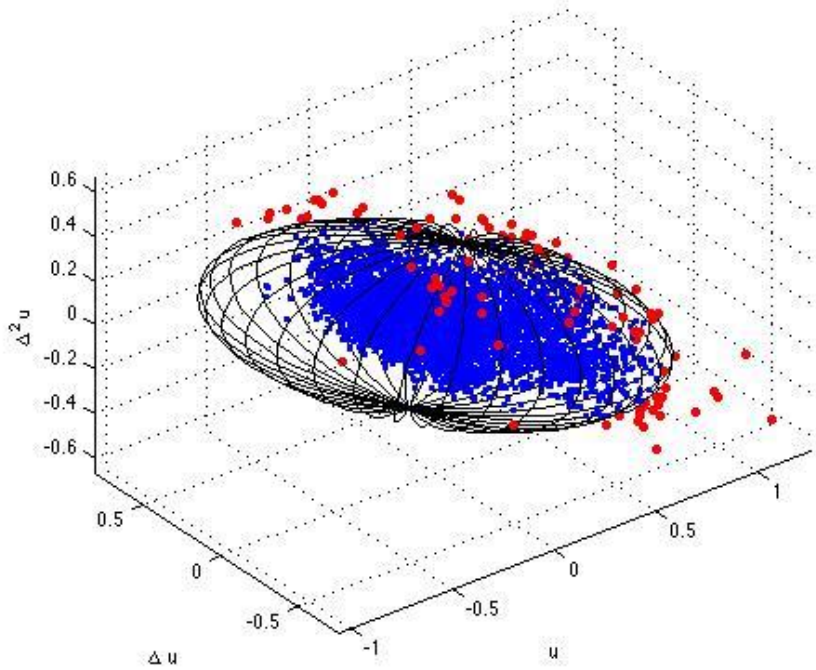


Figure 4.1 : The spikes which is located out side of the ellipsoid.

Each iteration has the following step:

- Calculate the first and second derivatives of velocity u ;
- Calculate the universal threshold as $\lambda = \sqrt{2 \ln N}$ from the number of data N ;
- Calculate the correlation between u and the second derivatives $\Delta^2 u$
- Produce an inclined ellipsoid of u , Δu and $\Delta^2 u$ with the angle calculated from the correlation between u – $\Delta^2 u$;
- Major and minor axes of ellipsoid are given by $\lambda \sigma_u$, $\lambda \sigma_{\Delta u}$ and $\lambda \sigma_{\Delta^2 u}$
- Identify the points that lie out side of the ellipsoid and replace them. Continue the above procedure until further spike replacement is not required.

Using a polynomial of best fit through the data on either side of the spike is a good function for the replacement of spike and the results shown for the ADV data the

best option are to use a third-order polynomial through 12 points on either side of the spike. All of the above condition is valid for ADV data with sampling frequencies from 25 to 100 Hz (Goring and Nikora, 2002). For comparing of despiking process by phase-space thresholding method the contaminated data and clean record was shown at Figure (4.2) (4.3) respectively. The outlier values which remove by despiking was marked by red points at Figure (4.2).

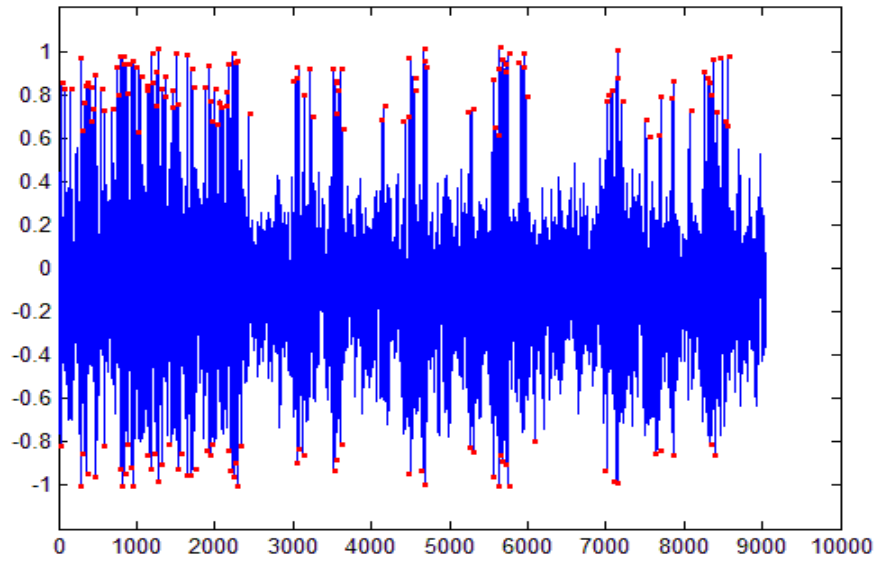


Figure 4.2 : The contaminated record data.

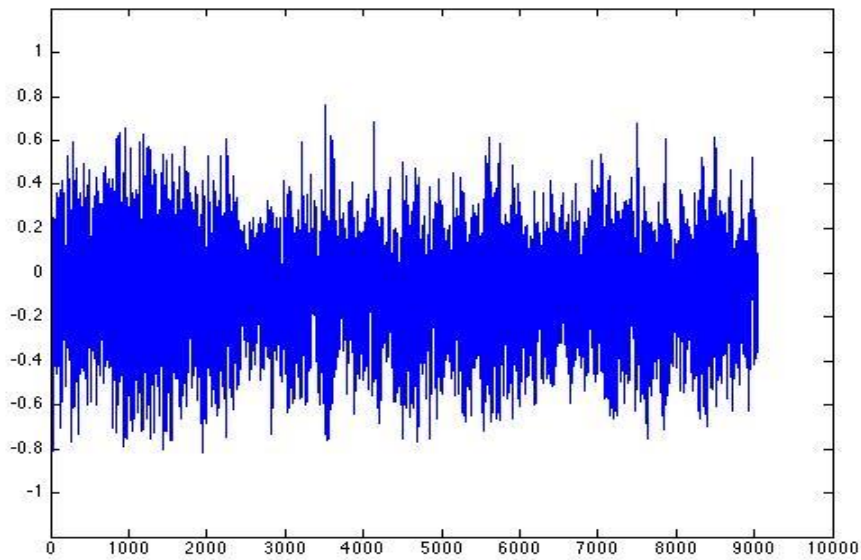


Figure 4.3 : The clean record data.

4.2 Reynolds Decomposition

When an instantaneous velocity record taken into consideration it can be decomposed into two parts. One of the major components is time-averaged velocity. Time-averaged velocity can be defined as below.

$$\bar{u} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{t_0}^{t_0+T} u dt \quad (4.1)$$

In which t_0 is an arbitrary time and T is the time over where the velocity averaged.

In fluid mechanics and the theory of turbulence, Reynolds decomposition is a mathematical technique to separate the average and fluctuation parts of a quantity and the instantaneous value of the velocity u written as

$$u = \bar{u} + u' \quad (4.2)$$

In which $\bar{u}$ is time-averaged velocity and u' is fluctuation of velocity (Sumer, 2007).

The significance of despiking process is clear at this stage to eliminate the fluctuation part from spike data.

4.3 Depth Average Velocity Calculation

As expressed above the first step of analysis was despiking of the data, which was already described at the first section of this chapter. This is followed the decomposition of the velocity measurements into the mean and fluctuation parts.

So as to determine the undisturbed the depth averaged velocity profile, firstly it was necessary to determine the discharge values those were measured at the sharp crested V-notch weir located at the upstream of the flume. In order to prevent misleading results regarding the measured discharge, after the initiating the flow in the flume, it is allowed to certain duration to elapse. In this way, the flow in the flume was stabilized and more reliable discharge measurements were obtained. Then using the measured discharge values, the unit discharges were attained by dividing the flow rate to width of the flume

After obtaining the unit discharge, the depth-averaged velocity was obtained dividing unit discharge by water depth. The water depth value where the flow is undisturbed and developed sufficiently was used in these calculations.

$$V_{un} = \frac{q}{h} \quad (4.3)$$

The non-dimensional Reynolds number that is one the most important factor to describe hydrodynamics is computed as defined below.

$$Re_D = \frac{V_{un} D}{\nu} \quad (4.4)$$

In which D is the diameter of the cylinder, V_{un} is the undisturbed flow velocity, and ν is the kinematic viscosity.

4.4 Turbulence Decomposition

In three-dimensional flow, the velocity measurements were decomposed and turbulence components for all direction were calculated. The u, v and w are the velocities of streamwise, vertical and lateral respectively.

$$v = \bar{v} + v' \quad (4.5)$$

$$w = \bar{w} + w' \quad (4.6)$$

and Turbulence Kinetic Energy of the flow which is the kinetic energy per unit volume of fluid for the fluctuating flow is defined as follow

$$k = \frac{1}{2} \rho (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad (4.7)$$

In order to give the experimental results in non-dimensional form turbulence kinetic energy was normalized by the square of the undisturbed depth averaged velocity ($\frac{k}{V_{un}^2}$). Similarly, the distance to the obstacles were expressed in non-dimensional for

by normalizing it by cylinder diameter ($\frac{x}{D}$). Likewise, the distance to the bottom was expressed by normalizing it with water depth ($\frac{z}{z_0}$).

4.5 Process of Flow Visualization

The videos that were obtained from flow visualization by laser sheet were monitored and quantified in the computer environment precisely. In order to do this, video records were transformed into photograph frames, which originally constitute the video.

Some characteristic particles were tracked along the consecutive photograph frames, and their path was marked based on the each frame. In this manner the path, which is followed by the particle, was created. However, it was necessary to quantify the marked motion in image environment. In order to do this the reference scales which was intentionally marked on the cylinder was utilized. After determined the point taken a snapshot from the scene and converted to Auto cad program. By used the same scale in each case drawn a straight line from the point to the cylinder and directly measured this length as a separation distance and this parameter was define as X_s . The image of flow visualization process at the Auto cad environment for upright case of cylinder and three different discharges was shown at Figure (4.4). The separation distance normalized by the cylinder diameter, plotted against the Re number.

The separation distance for each angle and discharges was shown at the Table (4.1) and Reynolds number near the cylinder for three discharges was shown at the Table (4.2).

As a result of this process for each angle the separation distances were obtained as can be seen from the Table. (4.3) below.

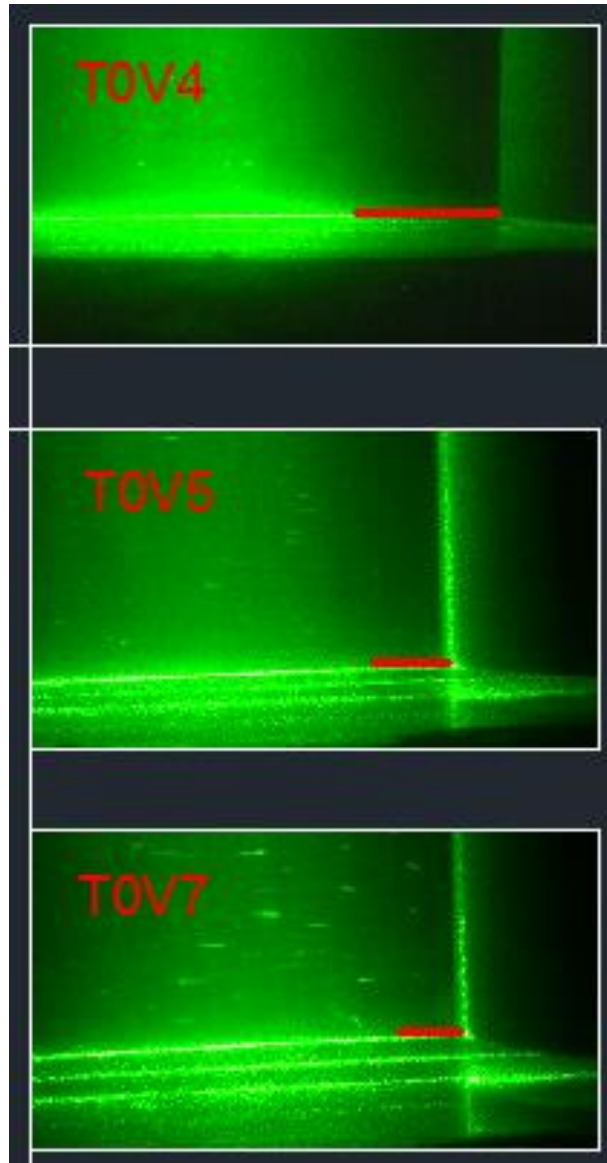


Figure 4.4 : Process of flow visualization at the Auto cad environment.

Table 4-1 : The separation distance.

Xs values real distance (m)			
θ vs Q	Q ₃	Q ₂	Q ₁
0°	0.044	0.043	0.019
15°	0.0417	0.036	0.014
30°		0.031	0.009
40°	0.031	0.0137	0.0134

Table 4-2 : Schedule of Reynolds number for three discharges.

Velocity and Reynolds number							
Case	Q (m ³ /s)	Depth (m)	Width (m)	D (m)	A	V _d =Q/A	Re _D
Q ₃	0.007	0.25	0.5	0.075	0.125	0.056	0.42*10 ⁴
Q ₂	0.017	0.25	0.5	0.075	0.125	0.144	1.08*10 ⁴
Q ₁	0.047	0.25	0.5	0.075	0.125	0.376	2.82*10 ⁴

Table 4-3 : Schedule of normalized separation distance and Reynolds number for each angle and different discharges.

(X _s /D) vs. Re _D			
θ Re _D	0.42*10 ⁴	1.08*10 ⁴	2.82*10 ⁴
0°	0.595	0.576	0.255
15°	0.557	0.487	0.186
30°		0.420	0.122
40°	0.419	0.183	0.179

5. RESULTS AND DISCUSSION

In this section of the study, the contour plots that were derived from the experimental velocity measurements are presented and interpreted. In order to facilitate the interpretation of the contour plots, the flow region at the downstream side is classified into three major zones as can be seen in Fig. (5.1). These are “near bed region”, “interaction zone”, and “near surface region” respectively. The major feature of the near bottom region is that in this region, bed generated turbulence and obstacle-induced turbulence (i.e. horse-shoe vortex) exist together. In the “near-surface region”, however, the major source of turbulence generation is mainly the lee-wake vortices that occurs as a result of strong separation due to adverse pressure gradient (i.e. the vortex shedding phenomenon). Within the interaction zone, the lee-wake vortices and horseshoe vortex strongly interacts with each other.

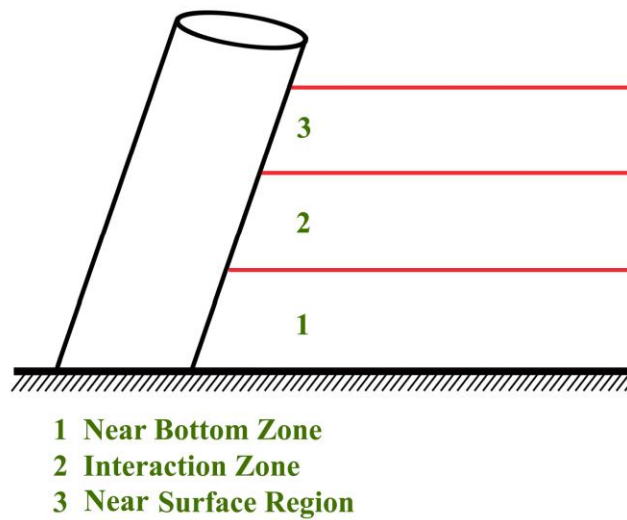


Figure 5.1 : Classification of the flow region at the downstream of the cylinder element.

5.1 The Influence of Inclination Angle on Streamwise Time-Average Velocity Characteristics

In this part of the study, the influence of inclination angle of the cylinder on the time-averaged velocity characteristics observed at the downstream of the element were discussed based on the contour plots that were derived from experimental measurements.

The variations of time-averaged streamwise velocity in the vicinity of the cylinder element are given in Fig. (5.2)-(5.3) for the tested five inclination angles and two flow conditions. As can be seen from the relevant figure, for the vertical case of the cylinder, the minimum values were observed in the range of $x/D \approx 2-3$. In this zone, the velocity values have negative sign which means that the direction of the fluid mass transport is towards upstream. At the downstream of the obstacle, negative velocity regions were observed consistently for both of the calculated Reynolds number ($Re=2.82 \times 10^4$ and $Re=1.08 \times 10^4$). This is very consistent with the present knowledge since the separation region at the downstream of the cylinder lies exactly in that area. In the inclined configurations however, these negative velocity regions are shifted towards the “interaction zone”. The most distinguished feature of the interaction zone is that, in this region the “horse-shoe vortex” located at near bottom zone is interacted with the “lee-wake vortices” which originates mostly from the surface-region. Other researchers also observed this kind of an interaction in recent studies (Sumer, 2014). Because of this interaction, considerable amount of kinetic energy is presumably extracted from the mean flow for turbulence production. This argument will further be justified by the “turbulent kinetic energy” and “mean kinetic energy” contour plots (Fig ((5.6)-(5.7)) and Fig ((5.12)-(5.13))). The detailed interpretations of these charts are given in the relevant sections. While the center of the deceleration zones are located within range of $x/D \approx 1.5-4.0$ for $Re=2.82 \times 10^4$, these are shifted closer to the cylinder, $x/D \approx 0.5-1.0$ for $Re=1.08 \times 10^4$. This implies that with the increasing Reynolds number the separation region is extended towards downstream. Likewise, with the increasing inclination angle the core of the deceleration zones, which exist at the interaction zone, are prone to shift towards downstream. However, it should be noted that this situation is not as clear as the influence of discharge.

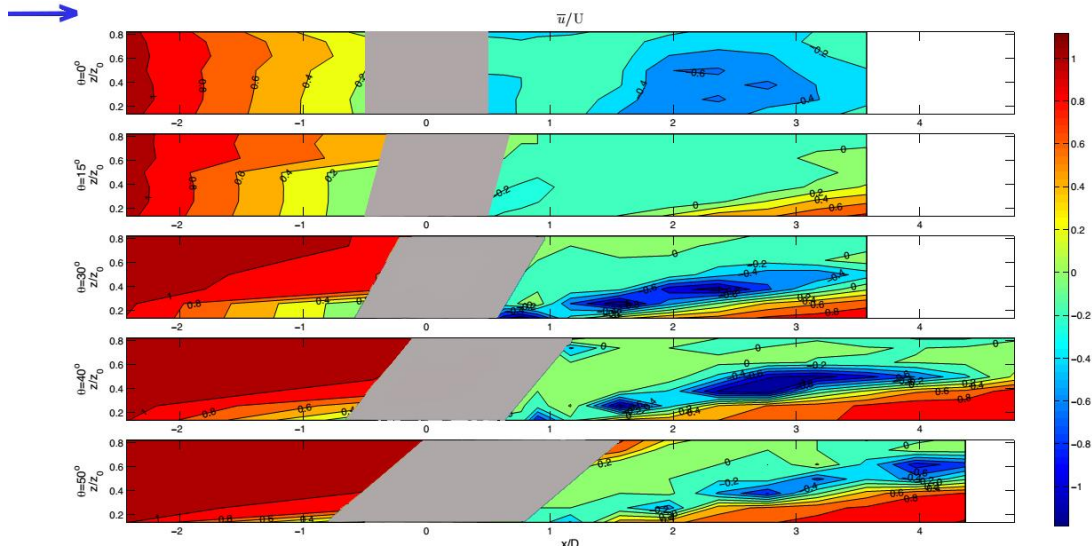


Figure 5.2 : The contour plots belonging to Streamwise Time-Averaged Mean Velocity for $Re = 2.82 \times 10^4$.

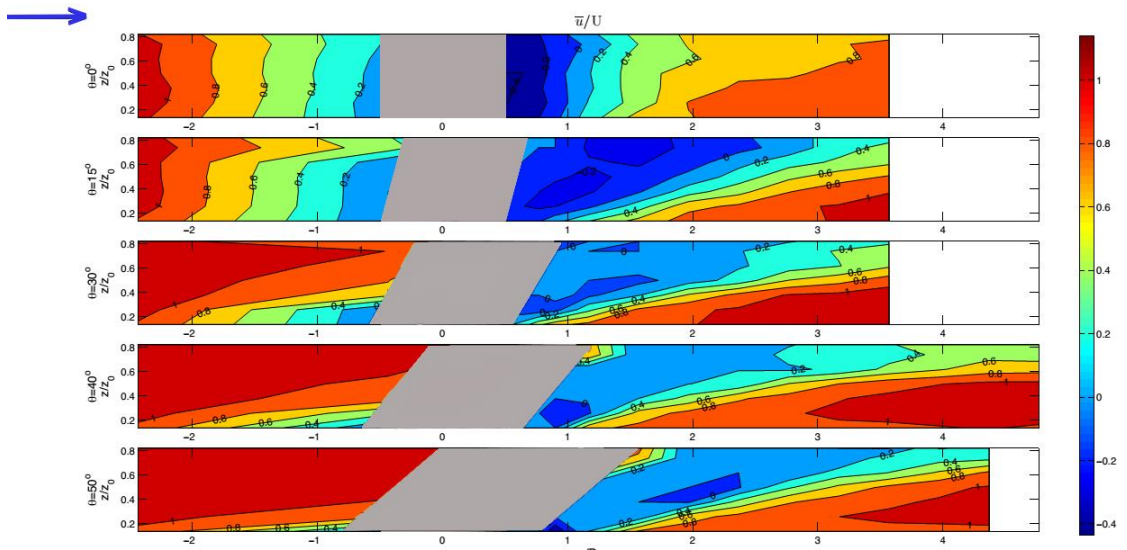


Figure 5.3 : The contour plots belonging to Streamwise Time-Averaged Mean Velocity for $Re = 1.08 \times 10^4$.

5.2 The Influence of Inclination Angle on Vertical Time-Averaged Mean Velocity Characteristics

The contour plots belonging to the vertical (wall-normal) time-averaged velocities in the vicinity of the cylinder elements are given in Fig. (5.4)-(5.5) for the tested five inclination angles and two flow conditions. As can be seen from Figure (5.4) and Figure (5.5), for both Reynolds number (i.e. $Re = 2.82 \times 10^4$ and $Re = 1.08 \times 10^4$), vertical time-averaged velocity values demonstrate that there is a significant vertical mass transfer within the interaction zone. According to Petersen (2014), as stated above, there are two large-scale counter-rotating streamwise vortices at the downstream of the cylinder. This was also further demonstrated and confirmed by Sumer (2015). Interestingly, the patterns of the vertical flow are slightly different for two different discharges. While the direction of the vertical flow was in the downward direction for higher Re number (i.e. $Re = 2.82 \times 10^4$) for certain regions, exactly at the same region the direction is in opposite direction for the lower Re number (i.e. $Re = 1.08 \times 10^4$). The most notable feature of these two charts is that the magnitudes of the vertical time-averaged velocity increase with the increasing inclination angle for both discharge values.

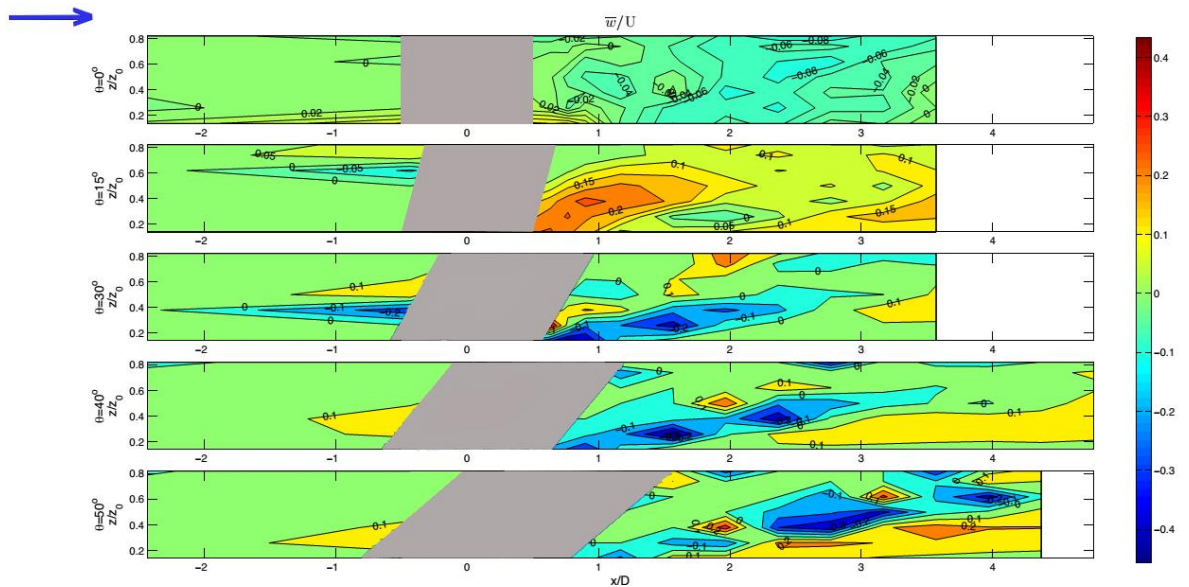


Figure 5.4 : The contour plots belonging to vertical Time-Averaged Mean Velocity for $Re = 2.82 \times 10^4$.

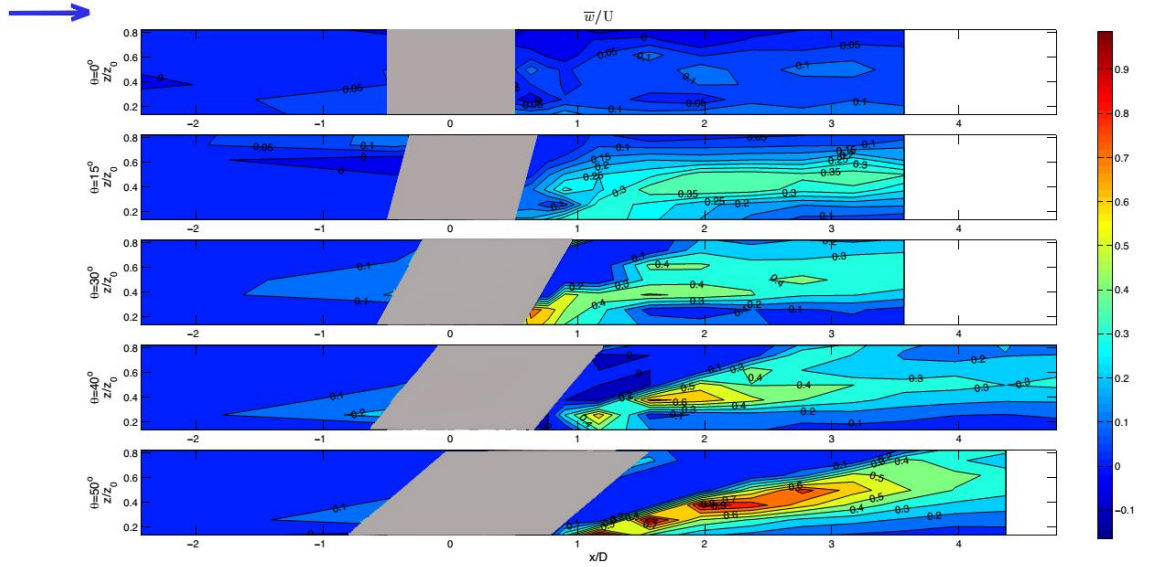


Figure 5.5 : The contour plots belonging to vertical Time-Averaged Mean Velocity for $Re = 1.08 \times 10^4$.

5.3 The Influence of Inclination Angle on Turbulence Characteristics.

The variations of turbulent kinetic energy patterns around the cylinder elements are as presented in Fig (5.6)-(5.7) for the tested five inclination angles and two flow conditions. For the sake of comparability, turbulent kinetic energy values are normalized by undisturbed mean kinetic energy. For both Reynolds number (i.e. $Re = 2.82 \times 10^4$ and $Re = 1.08 \times 10^4$) the highest turbulent kinetic energy regions were observed for the vertical cases. The centers of these regions are at $2(x/D)$ and $1(x/D)$ for $Re = 2.82 \times 10^4$ and $Re = 2.82 \times 10^4$, respectively. This denotes that for the vertical case of the cylinder with the increasing velocity, the core region of the turbulent kinetic energy shifts towards downstream since the separation is extended.

However, with the increasing inclination of the cylinder three distinct zones appear in the vertical sections. The highest turbulent kinetic energy values appear in zone 2 (i.e. interaction zone). In a way, this suggests that the bidirectional interaction between counter-rotating streamwise vortices and the lee-wake vortices enhance the turbulent kinetic energy values in the interaction zone. But towards the free-stream region, vortex shedding seems to be suppressed (i.e. suppressed) due to the decreased adverse pressure gradient with inclination.

When turbulent kinetic energy contour plots were all together considered it can be concluded that the inclination of the cylinder somehow lead to lower values of

turbulent kinetic energy at the downstream of the cylinder. This may somehow be expected. In fluid mechanics there is a commonly valid concept that if an immersed body has a more hydrodynamic form it generates less turbulent kinetic energy owing to weaker separation at the wake. When this idea is adapted to the inclined cylinder case, this means that with the increasing inclination angle, the form of the cross section (the cross-section orthogonal to the flow, i.e. ellipse) becomes more hydrodynamic. On the other hand, the perimeter length over the cylinder surface on which a boundary layer develops increases as well. Presumably, the elevated values of this length push the separation point around the cylinder further downstream. This results in the suppression of vortex shedding and a consequent decrease of the wakes. Another point is that the streamlines of flow approaching to an inclined cylinder tend to pass the cylinder in an orthogonal manner (Sumer and Fredsøe, 2002). However, when the streamlines pass the cylinder, the orthogonally is lost and streamlines obey the direction dictated by the flow, making the vortex shedding more difficult. Combining all these facts, the increase of cylinder inclination provides a more hydrodynamic form in spite of the fact that the volume of the submerged cylinder increases. This fact may have a practical significance in the design of the marine and riverine structures. More specifically, with the increasing inclination angle, presumably the inclined cylinder will generate less drag against the flow. However, this statement needs further quantification and should be deeper investigated.

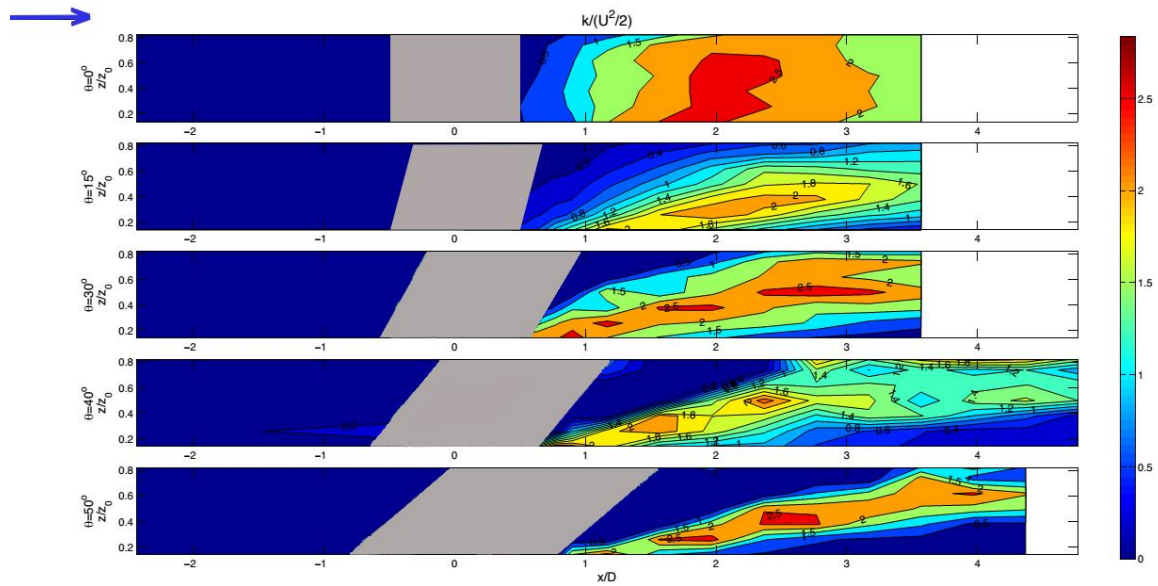


Figure 5.6 : The contour plots belonging to normalized turbulent kinetic energy for $Re = 2.82 \times 10^4$.

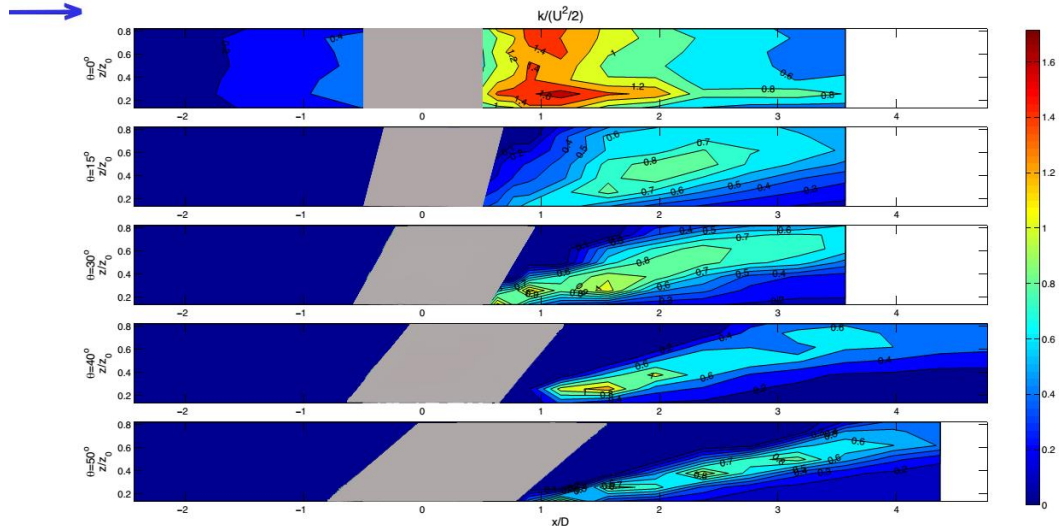


Figure 5.7 : The contour plots belonging to normalized turbulence kinetic energy for $Re = 1.08 \times 10^4$.

5.4 The Influence of Inclination Angle on Streamwise Turbulence Intensity Characteristics

The contour plots of the streamwise turbulence intensity values measured in the vicinity of the cylinder elements are given in Fig (5.8)-(5.9) for tested five inclination angles and two flow conditions. In parallel with the aforementioned assessments, for the vertical case of the cylinder, the streamwise turbulence intensities gradually increase towards downstream for the consecutive sections along the centerline since the vortices shed from the cylinder gets larger and more developed as they are convected downstream. However, with the increasing inclination of the cylinder three distinct zones appear in those sections. Likewise, the enhanced values of streamwise turbulence intensity at the downstream of the cylinder in a way confirm the strong momentum exchange between the “near-surface region” and “near-bottom region”. Moreover, generally speaking, when the vertical case and inclined cases are compared it can be concluded that streamwise turbulence intensity generated due to the presence of the cylinder gets less as the inclination increases. This conclusion is in complete conjunction with the previous one, considering that the most dominant contribution to turbulent kinetic energy comes from the streamwise component of the normal Reynolds stress.

Comparing Fig. 5.6 with Fig. 5.8, it can be seen that (especially for the vertical cylinder case) the turbulent kinetic energy starts to decay towards downstream after making its peak at 2D behind the cylinder. However, such decay is not seen in the

streamwise turbulence intensity plots, at least for the spatial limits of the present measurements. This directly implies that turbulent kinetic energy is not isotropic at the wake of the cylinder. This strong directionality of turbulence stems from the fact that transverse and wall-normal (vertical) turbulence fluctuations are dissipated by the flow more easily, but streamwise fluctuations survive longer. This is an important output of the present data.

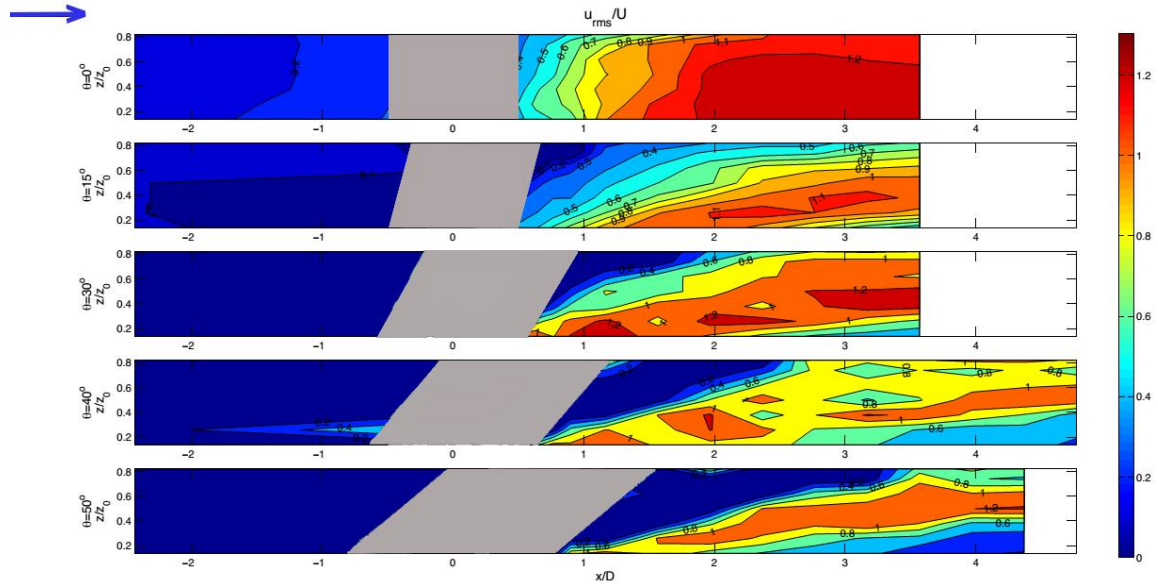


Figure 5.8 : The contour plots belonging to streamwise turbulence intensity for $Re = 2.82 \times 10^4$.

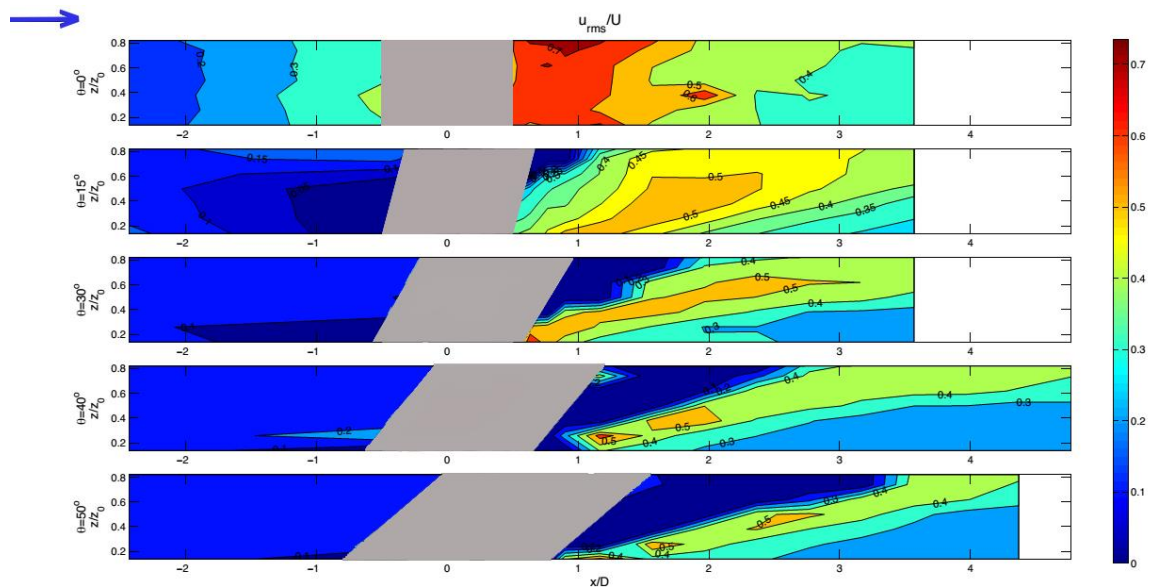


Figure 5.9 : The contour plots belonging to streamwise turbulence intensity for $Re = 1.08 \times 10^4$.

5.5 The Influence of Inclination Angle on Vertical Turbulence Intensity Characteristics.

The vertical (wall-normal) turbulence intensity contour values measured around the five different inclined cylinder elements are given in **Fig. (5.10)-(5.11)** for two different flow conditions. As can be seen from the relevant figures, for the vertical case of the cylinder, the vertical turbulence intensities gradually increase towards downstream for the consecutive vertical sections along the centerline for $Re = 2.82 \times 10^4$, as happened for streamwise turbulence intensities. However, for the lower values of Reynolds number (i.e. $Re = 1.08 \times 10^4$) three distinct zones (i.e. near surface region, interaction zone, near-bottom region) appear as previously happened only for the inclined cases. As stated above when the “vertical time-averaged velocities” at the downstream of the element are considered it was seen that the directions of the flow were in the downward direction for higher Reynolds number (i.e. $Re = 2.82 \times 10^4$) whereas the direction is in opposite way for the Reynolds number ($Re = 1.08 \times 10^4$). This state in a way confirms that the elevated values of vertical turbulence intensities occur within the interaction zone due to the strong interaction of the “lee-wake vortices” that occur in the near-surface region and the “horse-shoe vortex” that is generated in the near-bottom region. These two coherent structures interact and lead to strong momentum exchange between the “near-surface” and “near-bottom” regions. Furthermore, the changing direction of the time-averaged vertical velocities (i.e. changing momentum transport direction) suggest that the interaction between those two regions is a complex process and requires further investigation by more detailed numerical/physical models thoroughly. When the vertical turbulence intensities within the “near-surface region” is considered it can be concluded that with the increasing inclination angle, the values take lower magnitudes in the area closer to the water surface. This can be explaining by the previously explained fact that in this region the hydrodynamic section of the cylinder results in narrower wake region and this region is not expose to the effect of “horseshoe vortex” at all. The observed low vertical time-averaged velocity values in this region further validate this argument. In other words, the vortex shedding frequency at the downstream of the vertical cylinder is more or less unchanged along the length of the cylinder. The timing of the shedding frequency presumably overlaps along the depth at a certain extent (i.e. the correlation length is

relatively long, see Sumer and Fredsoe, 2006, section 1.2.2). At the upstream, with the increasing inclination, the extent of the separation distance lessens as proven by laser sheet measurements below. The diminishment in the separation distance in a way implies a reduction in the magnitude of the horseshoe vortex. Once again, comparing the contour plots of streamwise and wall-normal turbulence intensities, it is clear that decay of the turbulence is not isotropic. Vertical turbulence seems to decay much faster than streamwise turbulence. This can be attributed to the effect of bed-generated turbulence since it is known that the strongest component of turbulence in a wall-bounded shear layer is the streamwise component.

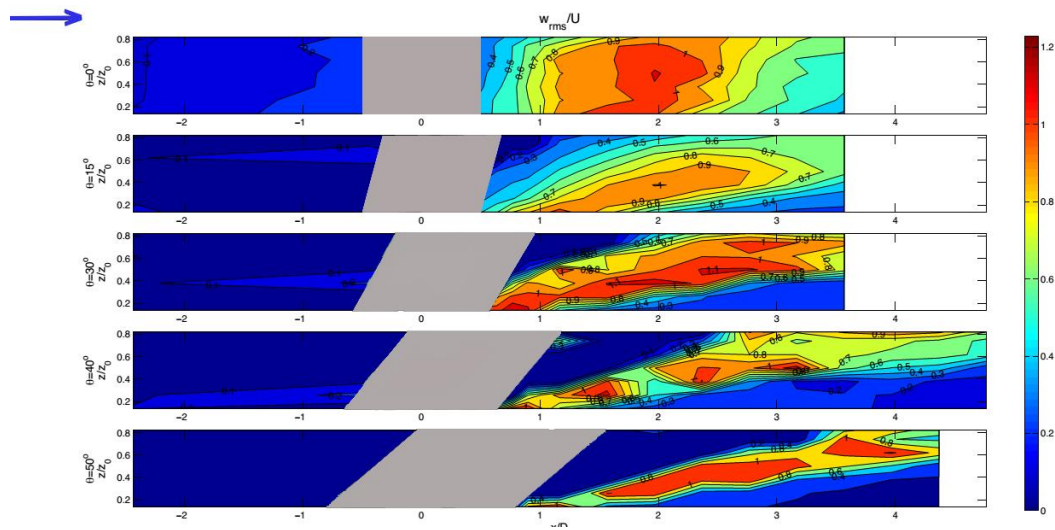


Figure 5.10 : The contour plots belonging to vertical turbulence intensity for $Re = 2.82 \times 10^4$.

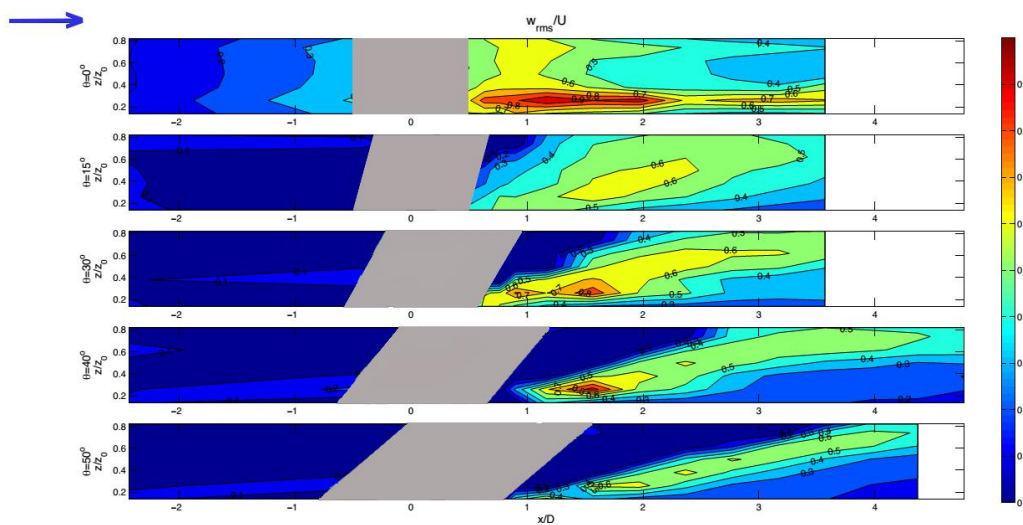


Figure 5.11 : The contour plots belonging to vertical turbulence intensity for $Re = 1.08 \times 10^4$.

5.6 The Influence of Inclination Angle to Mean Kinetic Energy

The contour plots of the mean kinetic energy values measured in the vicinity of the cylinder elements are given in **Fig (5.12)-(5.13)** for tested five inclination angles (i.e. 0° , 15° , 30° , 40° , and 50°) and two flow conditions ($Re= 2.82 \times 10^4$ and $Re= 1.08 \times 10^4$). From both of the figures, it is seen that for the vertical cases of the cylinder, the mean kinetic energy values are significantly lower compared to the inclined cases at the downstream of the cylinder elements. This can be explained by the fact that vertical cylinder case creates a stronger sheltering effect compared to the cases of inclined cylinders. This presumably led to higher contraction in the vicinity of the vertical element. Due to the enhanced contraction around the cylinder, the flow resistance around the cylinder will be higher, causing lower mean velocities. As can be seen from both relevant figures, with the increasing angles of the cylinder, the mean kinetic energy values increases. This would also further confirm that the inclined cylinder has a more hydrodynamic form (i.e. less sheltering effect) hence it may bring advantages in the practical application in terms of generating less drag force (Figure. 5.14).

In parallel with the above statement, the energy taken from the mean flow is expected to be used in turbulence generation. Indeed, the mean kinetic energy and turbulent kinetic energy contours coincide as a part of a jigsaw puzzle, one decrease when the other increases.

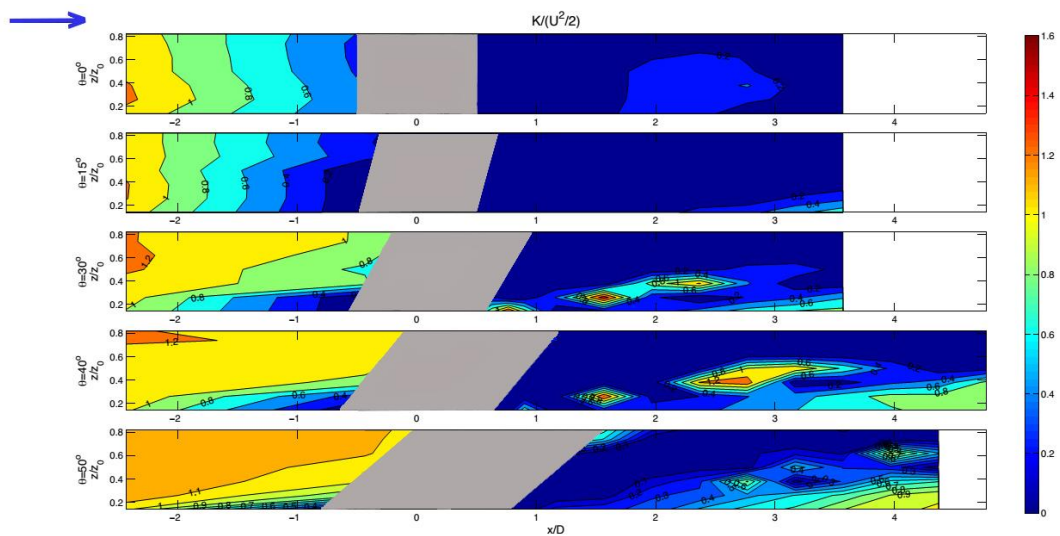


Figure 5.12 : The contour plots belonging to mean kinetic energy for $Re = 2.82 \times 10^4$.

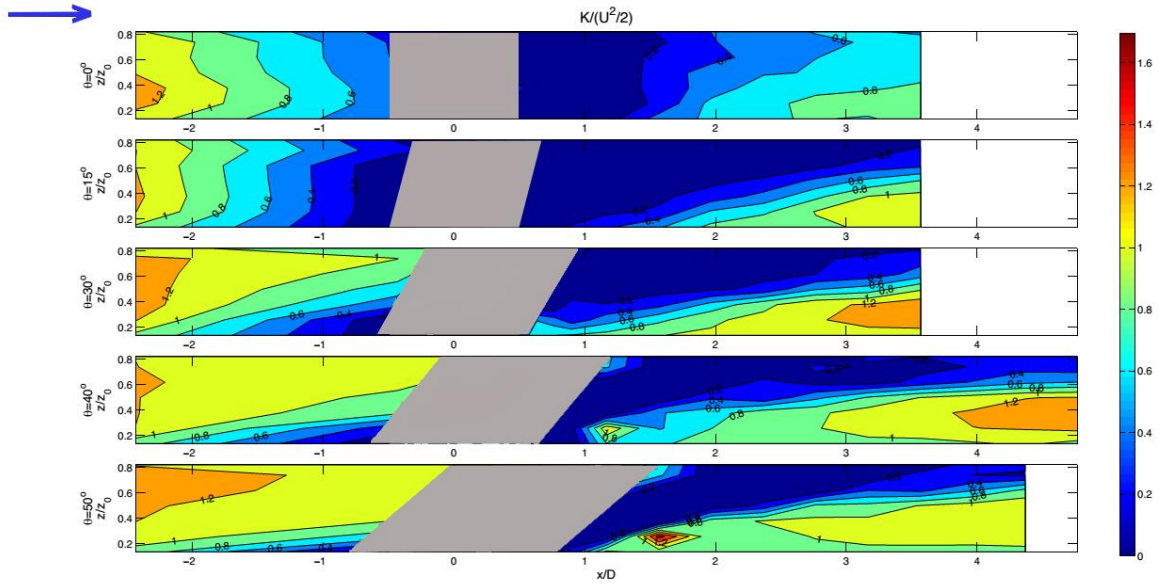


Figure 5.13 : The contour plots belonging to mean kinetic energy for $Re = 1.08 \times 10^4$.

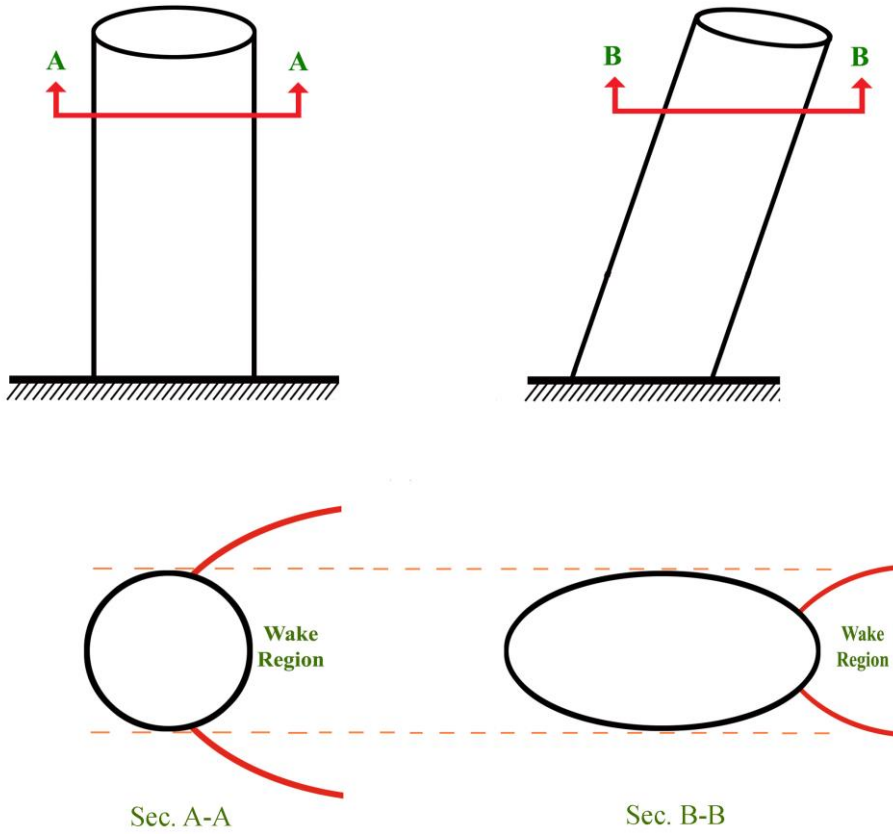


Figure 5.14 : Conceptual figure which compares the magnitude of the wake regions at the downstream of the cylindrical elements.

5.7 The Role of Inclination Angle on The Separation Distance at The Upstream of Cylinder

Separation distance at the upstream of the cylinder is recalculated as a non-dimensional parameter and plotted to respect of Re number. Due to the Figure that was obtained by Lagrangian process at the steady condition the separation distance decreases by increasing the Re numbers and inclination effect on the other means due to increasing the inclination angle and flow discharge the separation distance decreases. The highest value of the separation distance is 0.6D and was occurred at the lowest discharge of vertical case.

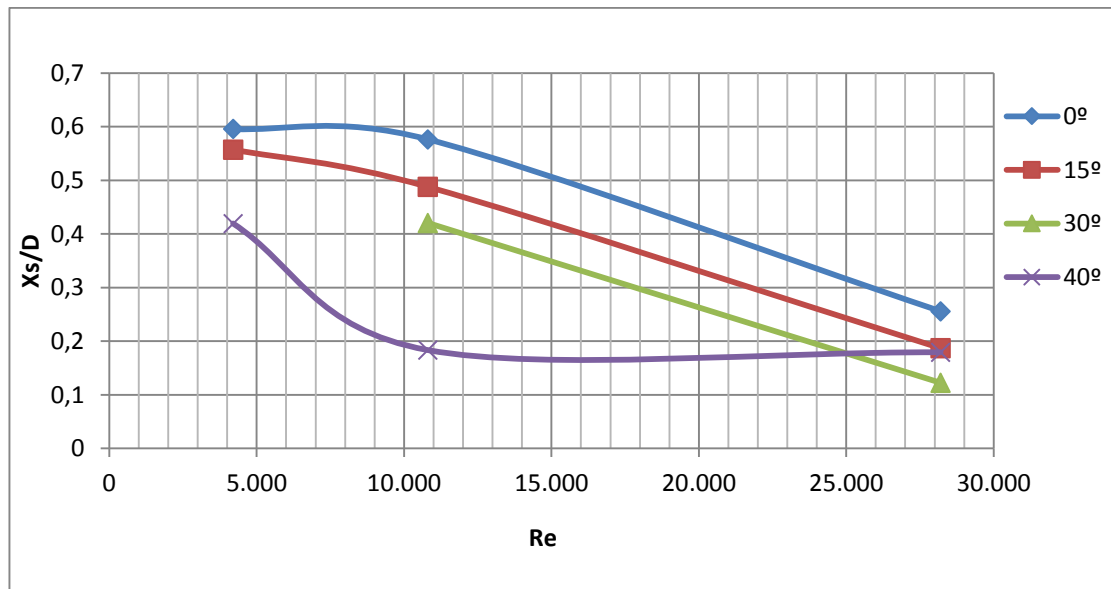


Figure 5.15 : The variation of X_s/D by the different Reynolds number.

6. CONCLUSIONS

In this study, flow and turbulence characteristics around inclined emergent isolated cylinders under steady flow conditions were experimentally investigated. The experimental findings revealed the following facts.

When the measured streamwise time-averaged velocity characteristics were assessed, it was seen that, for the vertical case of the cylinder, the minimum velocity values were located at the range of $x/D \approx 2-3$ downstream of the cylinder. In this region, the velocity values have negative signs implying that the direction of the mass fluid transport is towards upstream. On the other hand, for the inclined cases the center of the deceleration zones are located within range of $x/D \approx 1.5-4.0$ for ($Re = 2.82 \times 10^4$). These deceleration zones are shifted closer to the inclined cylinder for lower Reynolds Number value ($Re = 1.08 \times 10^4$), $x/D \approx 0.5-1.0$.

The time-averaged vertical velocity values showed that the magnitudes of the vertical time-averaged velocity increase with the increasing inclination angle for both discharge values. This may be explained by the fact that the inclination of the cylinder introduces a lag in the flow separation increasing away from the bed. In other words, a streamline located nearer to the bed passes the cylinder earlier compared to another streamline located above it. This leads to a vertical mass transfer and mixing.

Based on the measurements, it was seen that the highest turbulent kinetic energy regions were observed in a wider area for the vertical cases in both examined Reynolds Number. The centers of these contour regions were located at $2(x/D)$ and $1(x/D)$ downstream of the cylinder for ($Re = 2.82 \times 10^4$) and ($Re = 1.08 \times 10^4$), respectively. This implies that for the vertical case of the element with the increasing velocity, the center region of the turbulent kinetic energy shifts towards downstream since the separation region is extended towards downstream. More importantly, for the examined Reynolds Number values, the obtained turbulent kinetic energy characteristics patterns demonstrated that the inclined form of the cylinder is more hydrodynamic in spite of the fact that with the increasing inclination the submerged volume of the cylinder increases.

The strongest contribution to the turbulent kinetic energy production apparently comes from the streamwise component as shown above. Furthermore, it is observed

that the decay of turbulent kinetic energy occurs in wall-normal and transverse components quicker and streamwise turbulence survives longer. This leads to an anisotropic picture of turbulence since the residual turbulence is mostly the streamwise component.

The measured mean kinetic energy patterns revealed that for the vertical cases of the cylinder, the mean kinetic energy takes considerably lower values compared to the inclined cases at the downstream of the cylinder elements. This situation could be explained by the fact that vertical cylinder case creates a higher “sheltering effect” compared to the inclined cases. This may lead higher contraction effect around the vertical element. As mentioned previously several times, the inclination enhances the hydrodynamic form of the cylinder. When the picture of turbulent kinetic energy is compared with the mean kinetic energy, it can be seen that they overlap each other such that one increases whilst the other decreases. This is obviously due to the extraction of energy from mean flow for turbulence production by the cylinder.

For both of vertical cases the highest values of separation distances were observed at lower Reynolds number. It shows the higher velocity exposed more force and pushed the separation nearer to cylinder. At oblique case of cylinder by the reduction of sheltering effect separation distance reduces.

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APPENDICES

APPENDIX A: Process of flow visualization at the Auto cad environment.

APPENDIX A

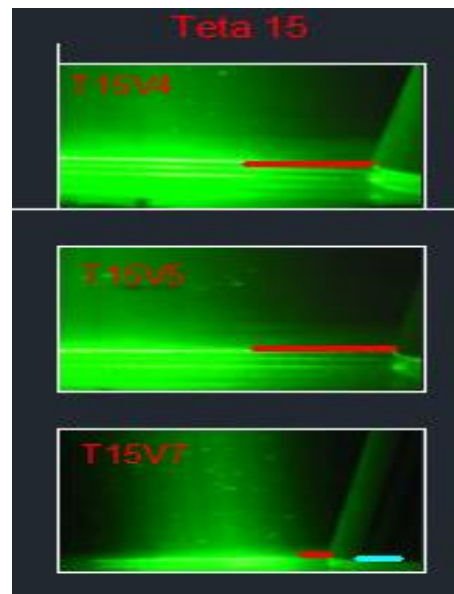


Figure A.1 : Process of flow visualization for inclination angle of 15° .

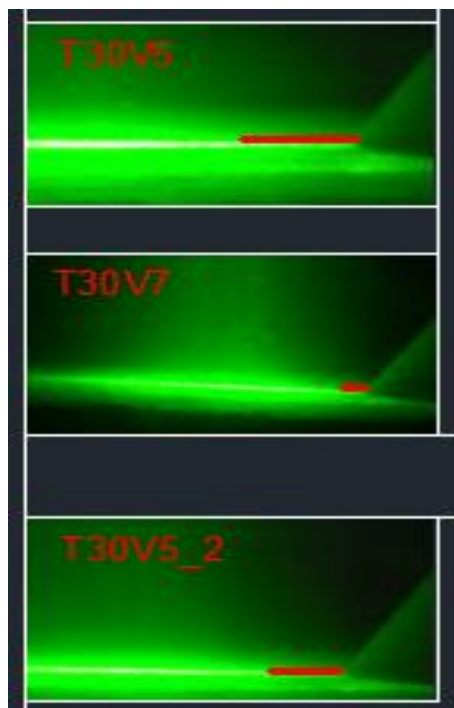


Figure A.2 : Process of flow visualization for inclination angle of 30° .

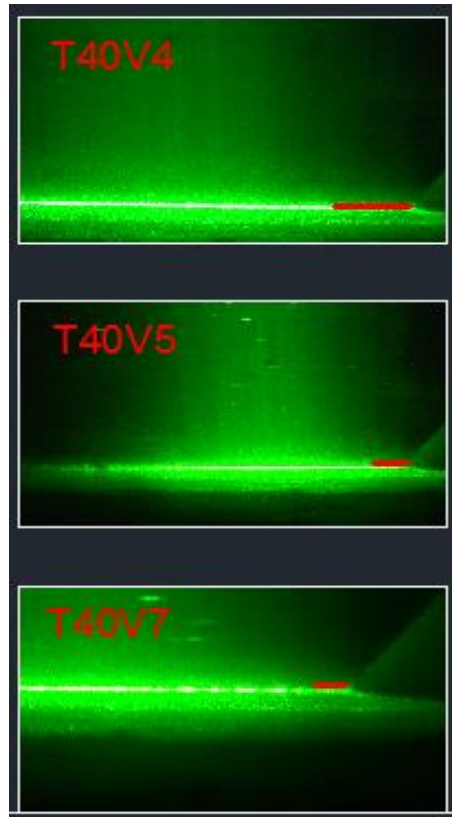


Figure A.3 : Process of flow visualization for inclination angle of 40° .

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