İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

NUMERICAL ANALYSIS INVESTIGATION OF HYDRODYNAMIC FORCES ON SUBMERGED PIPELINES

M.Sc. Thesis by
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THESIS SUBMISSION MAY 2010

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Date of submission : **03 May 2010**
Date of defence examination: **23 July 2010**

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THESIS SUBMISSION MAY 2010

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

MATEMATIKSEL MODELLEME
SUALTI BORULARINA ETKIYEN HYDRODINAMIC KUVVETLERIN INCELENMESI

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Tezin Enstitüye Verildiği Tarih : 03 Mayis 2010
Tezin Savunulduğu Tarih : 23 Temmuz 2010

Tez Danışmanı : Doc. Dr. Şevket ÇOKGÖR (ITU)
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THESIS SUBMISSION MAYIS 2010

FOREWORD

I would like to express my deep appreciation and thanks for my advisor. This work is supported by ITU Institute of Science and Technology.

May 2010

Devrim Erboyaci

Coastal Sciences and Engineering Department

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ABBREVIATIONS

GOM **:** Gulf of Mexico

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SUMMARY

In the emerging energy demand increasing time by time, all energy sources have a great importance and should be delivered in an optimum way using the best engineering practices. Deep water and ocean sources play an important role while attempting to meet this demand. Design and application of offshore pipelines should be not only cost-effective, but also reliable, because the failure of an underwater pipeline may both affect the environment and natural life severely and they are very difficult to solve.

When trying to find an applicable and effective way to design these structures, experimental studies give a great vision but they cannot cover most of the situations. Therefore, detailed numerical studies should be carried for each project including the worst scenarios. This thesis gives a brief overview to some of the factors that can be covered during such studies.

According to numerical analysis completed with a commercial code, parameters like the pipe diameter, deep water current velocity and pipe alignment position are investigated about their effects on the forces acting on the pipeline system. In the future studies, these analysis should be extended to other parameters for the system such as the inside pipe parameters and pipe material and unsteady analysis can be studied. Also case-specific studies can be carried out by simultaneously solving the statics of the system and updating the solution by considering the deformations in the system.

SUALTI BORULARINA ETKIYEN HYDRODINAMIC KUVVETLERIN INCELENMESI
MATEMATIKSEL MODELLEME

ÖZET

Zamanla artan enerji ihtiyacında tüm enerji kaynakları büyük önem kazanmıştır ve en iyi mühendislik uygulamalarıyla elde edilmelidir. Derin deniz ve okyanus kaynakları bu ihtiyacı karşılamada önemli rol oynamaktadır. Bu yüzden, deniz aşırı boru hatları tasarlanırken ve inşası gerçekleştirilirken sadece maliyeti değil güvenirliği de dikkate alınmalıdır, zira su altındaki boru hatlarında meydana gelebilecek arızalar hem çevreye ve doğal yaşama ciddi bir şekilde zarar verebilir, hem de çözümü oldukça zor problemlerdir.

Bu tür yapıları tasarlarken uygulanabilir ve en etkin yolu bulmaya çalışırken deney çalışmalarının büyük önemi vardır, ancak çoğu durumu kapsamaları mümkün değildir. Dolayısıyla, her proje için en kötü ihtimalleri de göz önüne alan ayrıntılı sayısal çalışmalar yapılmalıdır. Bu tezde, bu tür çalışmalarda kapsanabilecek bazı etkenlerin genel bir görünümü verilmiştir.

Ticari bir program kullanılarak yapılan sayısal analizlere göre, boru hattı sistemine etkiyen kuvvetler üzerinde etkisi olan boru çapı, derin su akımı hızı ve boru yerleştirme konumu gibi parametreler incelenmiştir. İlerleyen çalışmalarda, bu tür analizler zamanla değişen koşullar için tekrarlanabilir ve boru malzemesi veya boru içi hareketlerinin etkileri gibi sistem üzerinde etkisi olan diğer değişkenler de dahil edilebilir. Ayrıca sistemin statik durumunu da aynı anda çözerek ve sistem geometrisindeki değişimleri de göz önüne alarak çözümü güncelleyen duruma özel çalışmalar da gerçekleştirilebilir.

1. INTRODUCTION

The necessity of additional energy sources to meet the increasing demands, has resulted in searches for for new fossil deposits and studies for alternative energy sources. In respect of fossil deposits, interest and activities for offshore deposits has significantly increased, especially in deep waters. Deep water floating structures are considered to be a suitable solution. They have challenges as there are additional problems to contend with especially with respect to hazards related with environmental forces such as currents, winds, waves etc. to which the engineering structures are now exposed. Design of these pipeline structures depends on various factors such as pipeline materials, water depth, deep water currents, ground motions, and the seabed integrity in relation to geological and geo-mechanical properties.The engineering construction of an offshore pipeline is a complicated process and requires advanced technology. Although the pipeline may initially laid on the seabed, it eventually becomes buried over time due to the sediment deposition and the rate of deposition varies depending on the geo-mechanical and geological properties or characteristics.

The development of the technology of submarine pipelines has provided the possibility of conducting projects under extreme conditions with respect to water depth and environmental conditions. In these conditions long sections of spanning pipelines are often unavoidable. Free spans may occur due to the natural seabed irregularities present at pipe installation or they may develop during operation due to erosion, scour, or mitigation sand waves.

A submarine pipeline is a system of connected sections of pipe that usually transports crude oil or refined hydrocarbons. The pipe is laid on or buried in the seafloor. It typically ranges from 0.1 m to 1.0 m in diameter. The total length of a pipeline is dictated by the distances between the production platform(s) and the onshore or offshore destination(s) and by the route which poses the least risk in terms of offshore geohazards. Seabed canyons are often pathways for turbidity currents and debris flows. In some cases a route may include relatively deep and narrow canyon crossing; therefore, a section of the line in a free-span (suspended) condition between two support points. In other instances such as dredging and mining operations, the terminal points of the pipeline continually change. The placement of a fully or partially suspended pipeline below the ocean interface may offer the most practical solution.

The presence of submarine currents and wave induced flows may cause significant dynamic stresses to the free spanning pipe section. Amplified response due to resonant fluid-structure interaction, which involves large oscillations of the pipe, may damage weldings. The consequences can be fatigue of the material and reduction of the pipeline life. The sections of free spans may thus represent weak points of the transport system, as they have a low reliability.

1.1 Purpose of the Thesis

In this study, basic characteristics of free spanning pipe sections investigated. This span may occur whether from a bed-anchored system or due to a variation at the sea bed. Various numerical analysis are carried out in order to demonstrate a picture about the variation of different factors affecting the position and characteristics of the pipeline, such as the diameter of the pipeline, velocity of the deep water current and the distance of the pipe section to the sea bed.

1.2 General Information

Pipelines are one of the most practical and economical means for transporting liquids and slurries in quantity. Many ocean engineering activities involve the use of pipelines in the sea in conjunction with offshore oil development; offshore tanker unloading; deep ocean mining operations; beach replenishment; harbour and channel maintenance dredging; and in ocean construction using hydraulically placed fills.

Nearly 100% of the shallow water gas/oil product is transport to onshore processing facilities by pipelines. For instance, approximately 46,350 km of offshore pipelines exists in the GOM. In deep water the pipelines are still the most cost effective choice, regardless of design and installation difficulties.

In this study, an underwater pipeline is investigated with such a hypothetical configuration under water as shown in Figure 1. Water depth over the pipeline is assumed to be deep enough to dampen the surface wave effect, only deep water currents are considered.

Figure 2.1 : Typical anchored pipeline.

1.3 Literature Review

It is well known that the nature of sea states and its effect on sea wave height distributions and propagation is a complicated process. In fact on close examination of the real sea surface, one observes that the surface consists of variety of waves moving in different directions with different frequencies and heights.

Even before the pipelines, ocean and long structure issues were seen in the first trans-Atlantic cable, which failed in 1857. The variation in the wave-height distributions from place to place in relation to time history depends on fetch, wind velocity, duration of the wind flow, etc. are explained by Venkataramana et al. The problem of bending vibrations of a pipeline containing flowing liquid was in fact investigated several decades ago by Housner. In his studies, the pipe was idealized as a pinned beam and with the assumption of small displacements, a governing fourth-order partial differential equation was formulated with the third and fourth terms representing the centripetal and coriolis effects such that the Euler–Bernoulli's classical beam equation is recovered, if for theoretical purposes, the density of the flowing liquid is negligible. His analysis was however limited to surface transmission pipeline resting on supports at the two points, along the pipe.

Most of the previous studies belong to the late 1970s to mid 1980s, and they mainly address the issue of a buried pipeline or pile in an unstable soil slope which is moving.

Zakeri compiled a detailed survey and comparison of the available methods for estimating the drag forces on submarine pipelines. The literature shows that the problem of drag forces on pipelines has been investigated from two perspectives: a geotechnical approach and a fluid dynamics approach.

Demars (1978), Bea and Aurora (1982), Swanson and Jones (1982), Audibert et al. (1984), and Summers and Nyman (1985) all adopted the conventional approach to study the drag forces on buried pipelines in an unstable clay-rich slope. Their method disregards the strain-rate effects on the su, which is a well-established phenomenon. Calvetti et al. (2004) used the same approach to investigate the drag force on pipelines in unstable sand-rich slopes.

A series of model tests was carried out with a pipe dragged through liquefied sand under plane strain conditions at a velocity equal to 0.01 m/s. Although this is a very interesting investigation, it was not designed to study the debris flow impact problem. Georgiadis (1991) investigated the strain-rate dependency of the drag force on a pipeline embedded in a moving clay-rich soil mass and modified the conventional geotechnical approach. The investigation was limited to the use of only one type of clay and pushing the model pipe through the soil at very slow velocities ranging between 1.7E−5 and 1.5E−4 m/s. For piles, the literature includes the conventional geotechnical approach used by Wieghard (1975) and Towhata and Al-Hussaini (1988) for vertical cylinders in granular flow and mudflow, respectively.

The results as presented by Towhata and Al-Hussaini (1988) show a clear dependency of the drag force on the relative soilstructure velocity even within the lowrange of 0.01 to 0.12 m/s used in the experiments. However, the authors stated that the shear rate effects on the drag force are insignificant compared to the importance of soil water content and may be ignored. The strain-rate dependent geotechnical approach was adopted by Schapery and Dunlap (1978) and Vivatrat and Chen (1985) for mudflow around circular cylinders. Drag forces exerted by non-Newtonian fluid flow around objects based on fluid dynamics and rheology principles were first investigated by Pazwash and Robertson (1975).

In the fluid dynamics approach, they experimented with flat plate, ellipsoid, sphere and disc shaped objects (not a circular cylinder modelling a pipeline) immersed in kaolin clay solutions of different concentrations and obtained a shape factor for each object. Pazwash and Robertson (1975) used the shape factors to obtain the CD. Bea and Aurora (1982) also analyzed their experimental data using the fluid dynamics approach, but found that the method proposed by Pazwash and Robertson (1975) estimated significantly lower drag forces than those measured in their experiments. Chehata et al. (2003) experimented with a fixed horizontal cylinder immersed in a uniform granular flowconsisting of glass pellets and presented the drag force results in dimensionless form using the drag coefficient. The fluid dynamics approach was adopted by Pfeiff and Hopfinger (1986) to study the drag force exerted on a vertical cylinder moving in dense suspensions of polystyrene beads. These studies do not discuss how well the glass pellets and polystyrene beads may model actual soil behaviour. For the case of a buried pipeline or a pile in an unstable soil slope, the aforementioned geotechnical approaches (conventional and strain-rate dependent) provide a means to estimate the exerted drag forces on the onset or immediately after a landslide has been triggered. The approaches do not simulate the situation of a submarine debris flow impacting the structures. Previous studies using the fluid dynamics approach also have some significant limitations in addressing the submarine debris flow impact on pipelines (e.g. Pazwash and Robertson, 1975 did not experiment with a circular cylindrical object and Pfeiff and Hopfinger, 1986 worked with suspensions of polystyrene beads rather than soils in their experiments).

The physics of submarine debris flow impact on objects remains largely unaddressed in the literature. However, Norem et al. (1990) introduced an approach to the physics and dynamics of submarine slides and debris flows addressing the stresses generated within the flow as well as on the base. This approach may be used to some extent to estimate the drag on a flat object.

Several aspects of free span pipelines are presented in the literature. Halse presents a dynamical analyses of a free span pipeline in uniform and in sheared flow. A recent study by Hansen et al. examined the vibrations of a free span pipeline located in the vicinity of a trench. The objective of the work was to extend the validity of Guidelines 14 of Det Norske Veritas (June 1998) concerning free span pipelines.

2. THEORETICAL CONSIDERATION OF SUBMERGED PIPELINES

2.1 General Characteristics of Submerged Pipeline

Large numbers of pipes have been laid on the seabed in recent years in connection with the extraction of oil and gas at sea. The pipes are either laid freely on the seabed, possibly with fixing points arranged at intervals from each other, or are buried in the seabed and covered. The prior art describes solutions in which floating elements are used in connection with the laying of a pipeline. However, these floating elements do not serve as buoyancy elements for a floating, permanently anchored pipeline. They are removed after the pipeline has been positioned on the seabed. In areas in which the seabed is very uneven with high peaks and deep, wide depressions (valleys) at great depths, the existing pipe-laying methods cannot be used.

The buoyancy for the pipeline is provided by floating elements and/or floating material arranged at intervals and in a mainly uniform layer around the pipeline, possibly in combination with weights or sinker material, and that the pipeline is anchored to the seabed by stays or anchor lines arranged at intervals.

In order to keep the pipeline floating, most generally buoyancy elements are used. The buoyancy elements can be in the form of dense, solid elements of steel or other metallic material or they can be made of foamed plastic material, for example polypropylene or PVC.

The anchor point in the seabed may be gravitation anchor, pillar anchor, suction anchor, plate anchor or penetration anchor. The pipeline can have one or two, or possibly also more, anchor lines for each anchor point. Moreover, the lines/stays can be in the form of fibre rope of aramid, polyester, etc., steel wires, steel chains or rigid stays of steel, titanium, composites, etc.

Oscillations (vibrations) induced by the local water currents present a major problem which must be solved for floating pipelines. Over time, the oscillations can lead to fatigue and in certain situations to uncontrolled excess loads in connection with natural oscillations, which can result in fracture in the worst case scenario. One way of controlling the oscillations is by axial tension to the pipeline. When the pipeline is laid, filled with water, it is most expedient for it to be in a straight line. When the pipeline is emptied, the axial tension will, as a result of the net buoyancy of the pipeline itself and the buoyancy elements, produce the most favourable oscillating frequency situation, i.e. in connection with high natural oscillations.

Another way of controlling the oscillations is by varying the distance between the support points (pipe sections/pipe spans). These distances must be chosen so that the natural oscillations of the pipe sections will be higher than the threshold value of the excitation frequency generated by the surrounding water current.

The underlying theory shows that pipe sections of different lengths have different natural oscillations. As the pipe sections will "prefer" to oscillate at their own natural oscillations, neighbouring sections of different lengths will contribute to damping each other's oscillating amplitudes. In areas with varying water current speed along the pipe, the length of the sections can be adapted to the local current speed and thus increase the pipe's fatigue life. The tension in the pipeline and the distance between the support points should preferably be co-ordinated and optimised in order to achieve minimal stress in the pipeline.

2.2 Engineering Aspect

The total pipe system rigidity is represented by a combination of tension (cable power) and bending power. As the distance between the support points increases, the cable power will be dominant. The maximum static sag/deflection as a consequence of buoyancy/weight for an anchored pipe can be calculated purely from the point of view of the cable using the expression of deflection:

$$W = \frac{qL^2}{8 \cdot N_{eff}}$$

(2.{ SEQ Figure * ARABIC })

where W= deflection of the free span, q= distributed load, L = length of the span and N_{eff} = tension in the pipe.

It can easily be seen from the above formulae that the natural frequencies of a floating, anchored pipe can be changed by, among other things, changing the effective tension N_{eff} and the length L between the anchor points. On the other hand, it is necessary also to take deformation (bending outwards) and the bending moment of the pipe into consideration.

If the bouyant forces are more effective, the deformation W of the pipe takes place in upward direction.

The force acting on a pipeline under a deep water current can be evaluated as the flow around a cylinder, such as a bridge pier, as fas as the geometrical changes are discarded. The drag force for a cylinder on which a flow is imposed is given as;

{ QUOTE $F_D = \frac{1}{2} C_D \rho V^2 A$ } **(2.{ SEQ Figure * ARABIC })**

where C_D is the drag coefficient that can be determined experimentally.

For the range of Re numbers normally encountered in practice, about Re ~ 104, the contribution of the friction drag to the total drag force is less than 2 - 3%. So the friction drag can be omitted in most of the cases, and the total mean drag can be assumed to be composed of only one component, namely the form drag.

The pressure distribution obtained from the potential flow theory is given as,

{ QUOTE $[p - p]_1 0 = 1/2\ \rho V^{\dagger} 2\ (1 - 4 \sin^{\dagger} 2 \emptyset)$ } **(2.{ SEQ Figure * ARABIC })** where po is the hydrostatic pressure. The main characteristic of the measured pressure distributions is that the pressure at the rear side of the cylinder (i.e., in the wake region) is always negative (in contrast to what the potential-flow theory gives). This is due to separation. The pressure on the cylinder remains practically constant across the cylinder wake. This is because the flow in the wake region is extremely weak as compared to the outer-flow region. The drag coefficient as a function of Reynolds number is given by Schlichting (1979) as shown in Figure 2.2.

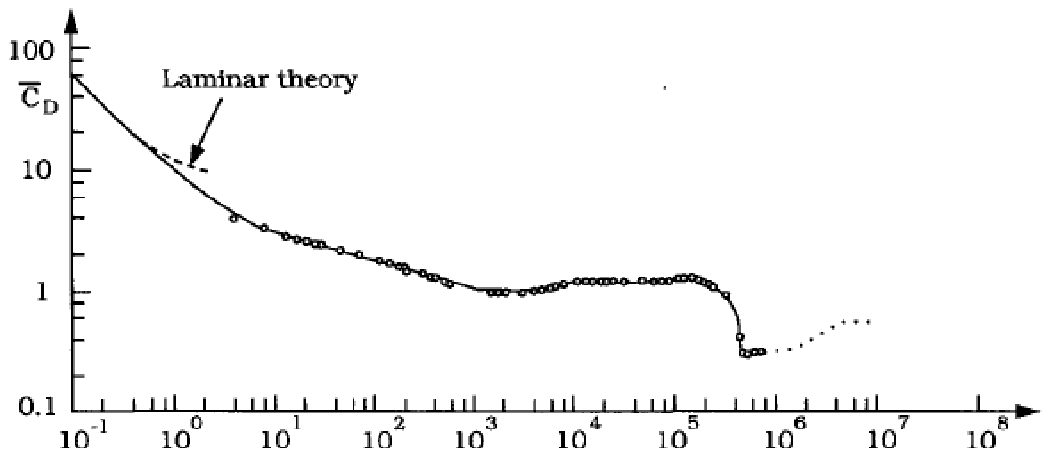

Figure 2.2 : Drag coefficient for a smooth cylinder as a function of Reynolds number.

The changes in the flow caused by the wall proximity influence the forces acting on the cylinder. In addition to the changes in drag and lift forces, they also show an oscillating character. Sümer and Fredsoe (2006) clearly stated that the general trend is that the drag coefficient decreases with decreasing gap ratio near the wall. The differences between the various experiments may be attributed to the change in the Reynolds number. Cp increases in a monotonous manner with increasing e/D up to a certain value of e/D, and then it remains reasonably constant for further increase in e/D. This behaviour has been linked by Zdravkovich (1985) to the thickness of the boundary layer of the approaching flow. At lower gap ratios the cylinder is embedded partly in the potential flow region and partly in the boundary layer of the incoming flow. Therefore, in the case of a bed or wall, the mean flow around a near-wall cylinder is not symmetric.

3. NUMERICAL MODELLING AND DISCUSSIONS

3.1 Mathematical Modelling

The main focus of this chapter is to give the underlying theory used in the solver and to present the results obtained. Conservation equations for mass and momentum are solved for the basic fluid flow acting on the pipeline. As the flow does not involve any heat transfer or compressibility for this stage, no additional equation is solved for energy conservation. Standard k-ε model is used with standard coefficients for turbulence modeling.

General form of conservation of mass and momentum equations are given as follows;

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m$$

(3.{ SEQ Figure * ARABIC \r1 })

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\overline{\overline{\tau}}) + \rho \vec{g} + \vec{F}$$

(3.{ SEQ Figure * ARABIC })

The choice of turbulence model is made according to the simplicity of the problem, as the problem is solved in two dimensional and does not have too much complexity, k-ε model is preferred.

3.2 Definition of the Problem

In order to analyze the free spanning pipeline floating over the bed, initially two models as three-dimensional and two-dimensional are constructed, and it is seen that the problem can be simplified by using two-dimensional model as the geometry does not change through pipe alignment. Initial three dimensional model is shown in Figure 3.1, having the left side as inlet for deep water current and applied quadrilateral grid is shown in Figure 3.2 in the vicinity of the pipeline.

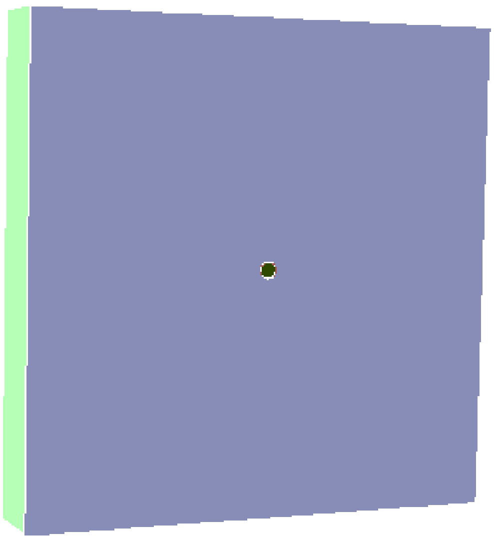

Figure 3.1 : Three dimensional modelling of the problem.

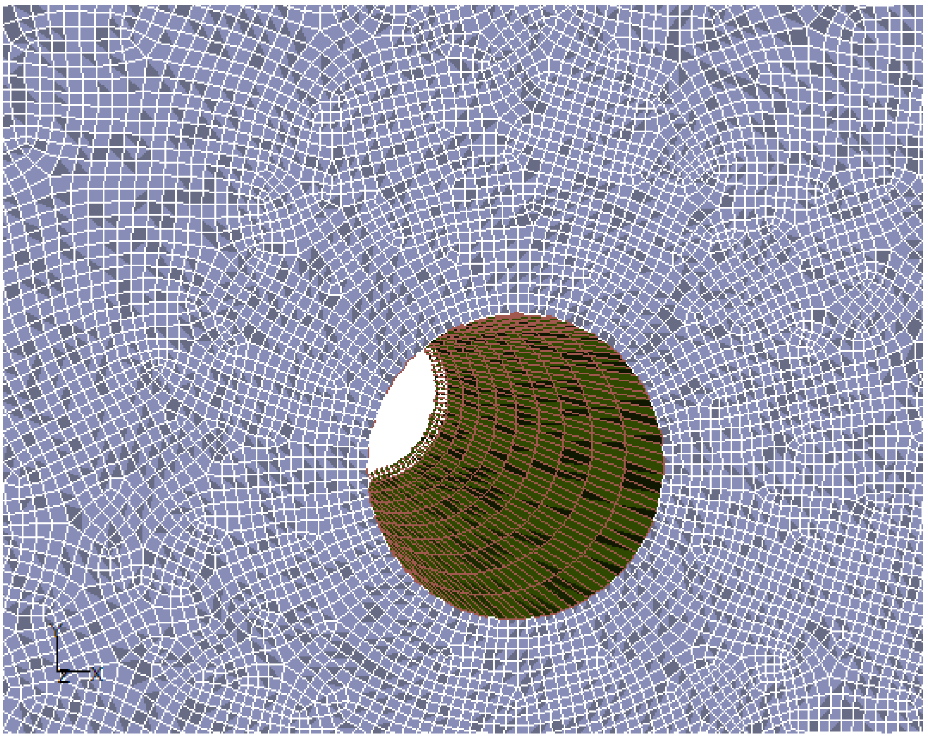

Figure 3.2 : Quadrilateral grid used in the model.

Due to unnecessary computational load imposed by three-dimensional geometry and the possibility to reduce the system, the problem is simplified by taking a plane normal to the pipe axis and two-dimensional studies are carried on this layout. Typical studied geometry is given in Figure 3.3. The grid number used is in the order of 10^5 and varying between the cases. Denser grids are used around the pipe and boundaries and coarser ones are used in the free stream region.

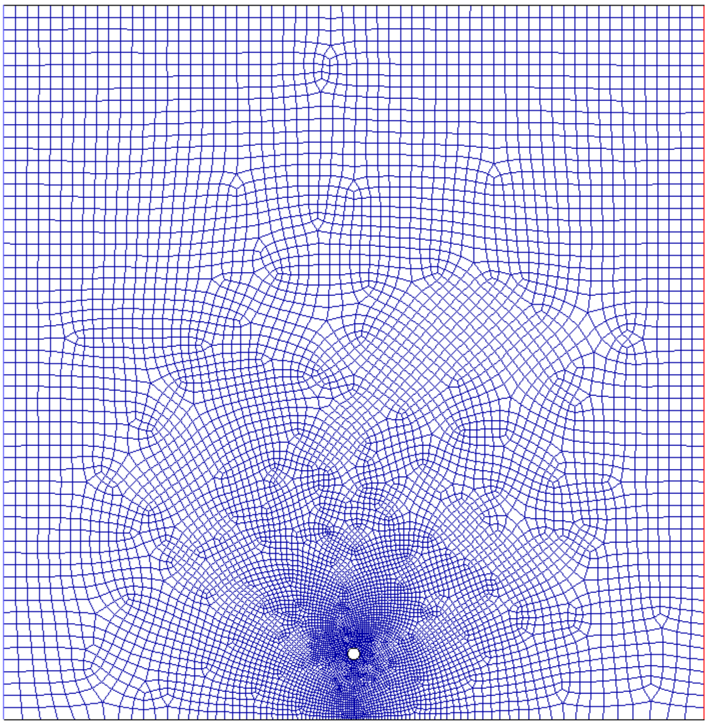

Figure 3.3 : Two-dimensional model of the problem.

3.2.1 Initial and Boundary Conditions

For all domain, inlet velocity value is given as initial condition. Pressure reference location is given far away from the domain not to force the system to a specific pressure. Boundary condition for inlet is given as velocity inlet and outlet condition is pressure outlet. Walls used in the system have slip boundary condition and the pipe surface has no-slip boundary condition.

As the pipe surface is a regular shape, quadrilateral grids are used with refinements near the pipe.

3.2.2 Solver Settings

Two-dimensional, pressure based, steady, cell based, implicit solution is applied for all the cases. For wake or vortex formations because of the pipe structure, standard k-e turbulence model is applied as the viscous model. SIMPLE pressure-velocity coupling approach is applied for pressure solution.

3.3 Test Cases

As mentioned above, three different variable types are investigated. Initially the effect of the flow is investigated on variable pipe diameters. In the second set, the deep water current velocity is changed while having no bed effect. As a third stage the effect of the distance with respect to sea bed are analyzed.

3.3.1 Case A: Variable Pipe Diameter

Depending on the amount carried by the pipeline, diameters used show a great difference between the applications. Therefore, the diameter effect on the pressure distribution acting on the pipeline is analyzed. A range of 0.20 m to 2.00 m is used with 0.10 m increments, where the current velocity is kept constant as 0.5 m/s. The forces acting on the pipeline in x direction, in other words normal force is given in Figure 3.4 with respect to pipe diameter. The velocity distribution and the pressure distribution are shown in figures 3.5 and 3.6 respectively. These plots are given for pipe having 1.0 m diameter and with an current velocity of 0.5 m/s. In this case the pipe is assumed to be far enough from the bed.

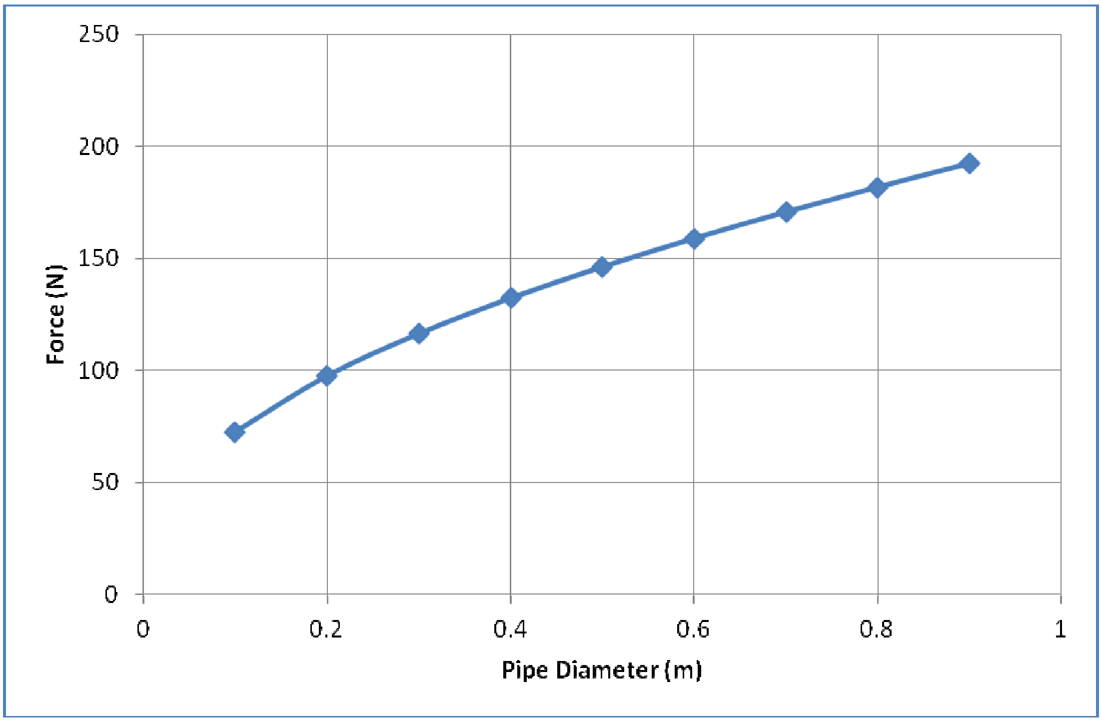

Figure 3.4 : Force acting on the pipeline in normal direction.

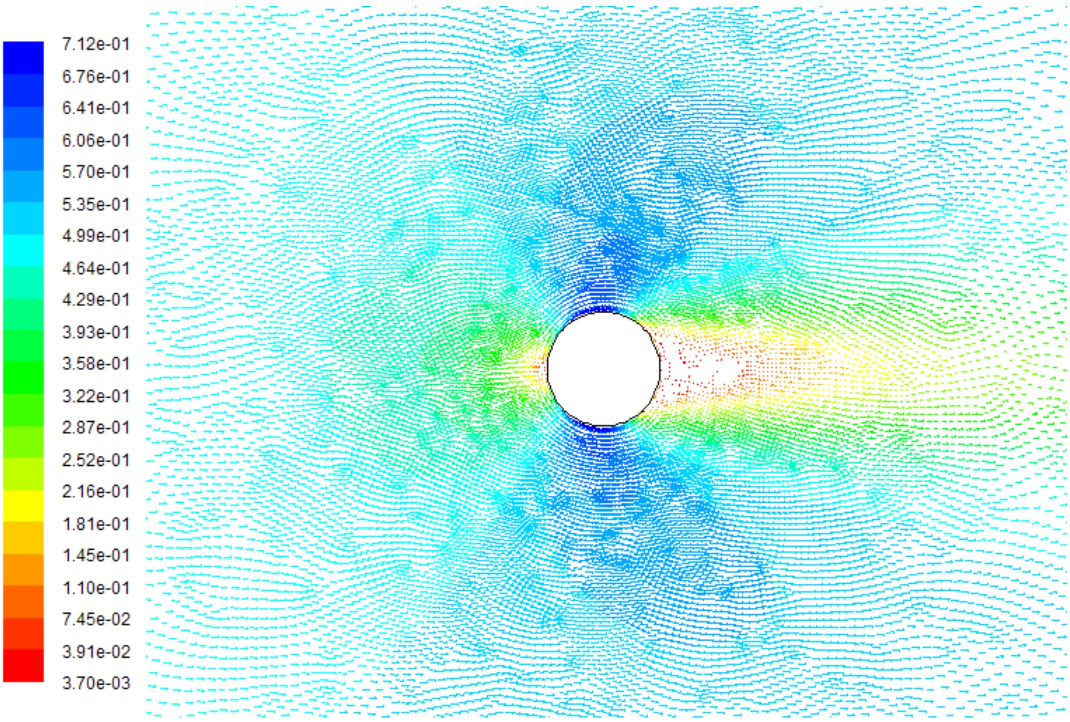

Figure 3.5 : Velocity distribution around the pipe (m/s).

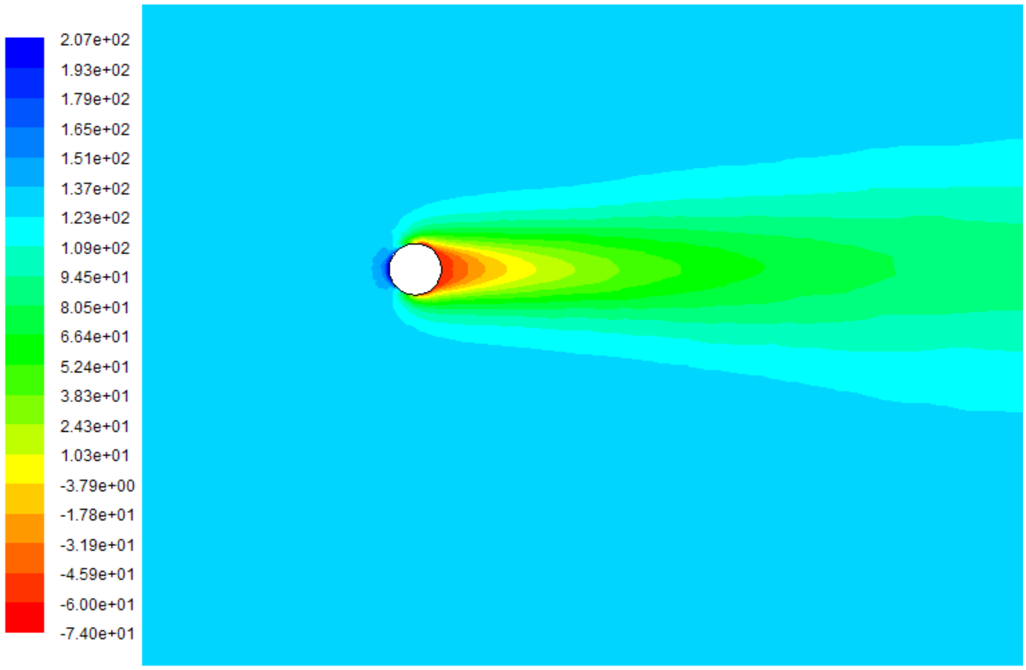

Figure 3.6 : Pressure distribution around the pipe (Pa).

3.3.2 Case B: Variable Water Current Speed

Depending on the location and depth of the pipeline, it may be exposed to different deep currents. Therefore, the current velocity acting on the pipeline is analyzed. A range of 0.10 m to 1.00 m is used with 0.10 m increments, where the pipe diameter is kept constant as 1.0 m. The forces acting on the pipeline in x direction, in other words normal force is given in Figure 3.7 with respect to pipe diameter

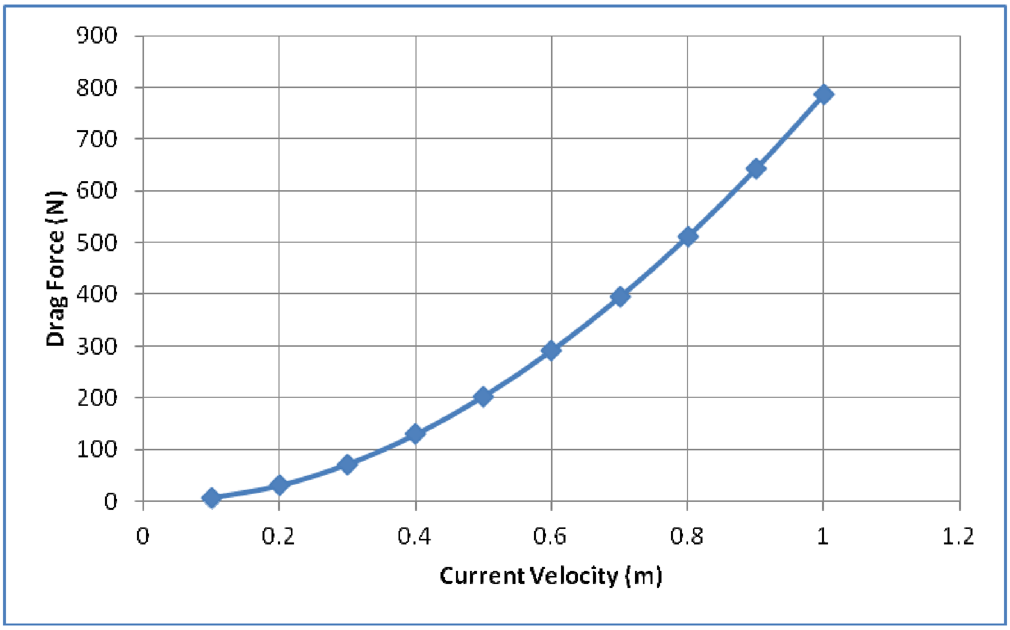

Figure 3.7 : Force acting on the pipeline in normal direction (N).

3.3.3 Case C: Variable Distance with respect to Sea Bed

The distance of the pipeline from the sea bed plays an important role, because the changes in the bed geometry are expected changes and this factor should be considered in designing the pipeline. For a fixed diameter size of 1.00 m, different distances are analyzed and changes in horizontal and vertical forces are shown in Table 3.1.

Table 3.1: Variation of net forces on the pipeline with changing depth

Distance to bed (xD)	Force in axial direction (N)	Force in vertical direction (N)
1	141.06	2.72
2	155.80	2.54
5	158.99	2.15
10	154.50	9.29
20	160.88	4.08

It can be suggested that, for the desired configuration of pipeline layout, detailed and unsteady analysis should be performed to consider the maximum forces acting on it. As the flow is no more symmetrical with respect to pipe axis, vertical forces become more important. The pressure distributions for D, 2D, 5D, 10D and 20D distances are given below in Figure 3.8-3.12. These analysis are also completed in 0.5 m/s, optimum bed distance should be determined according to site-specific conditions.

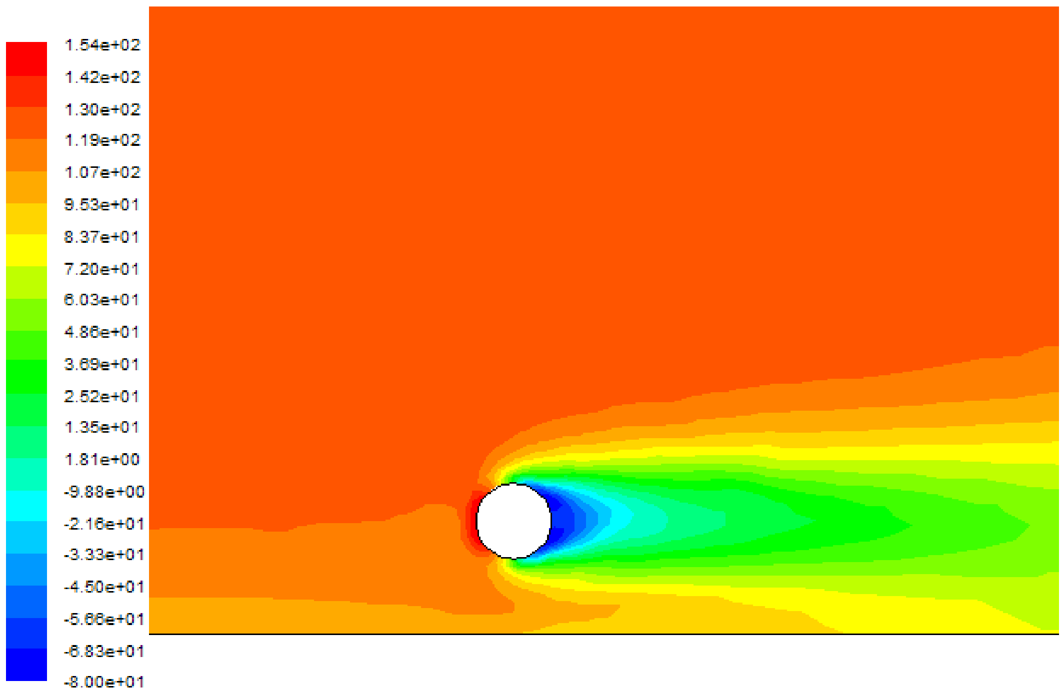

Figure 3.8 : Pressure distribution around the pipeline for D distance (Pa).

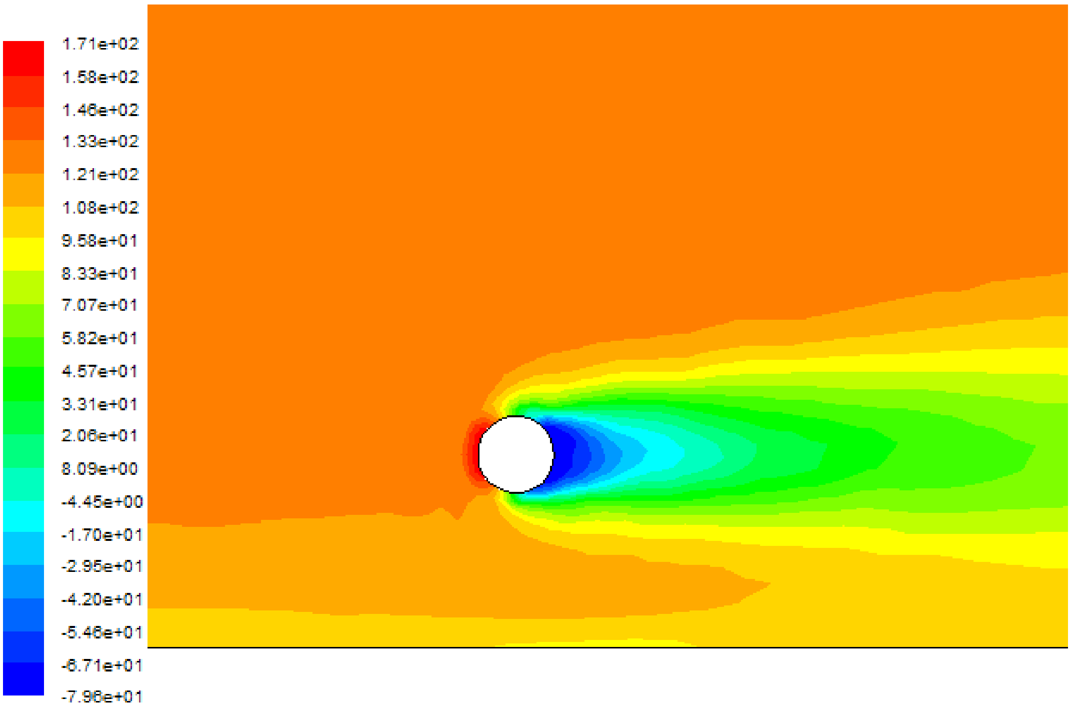

Figure 3.9 : Pressure distribution around the pipeline for 2D distance (Pa).

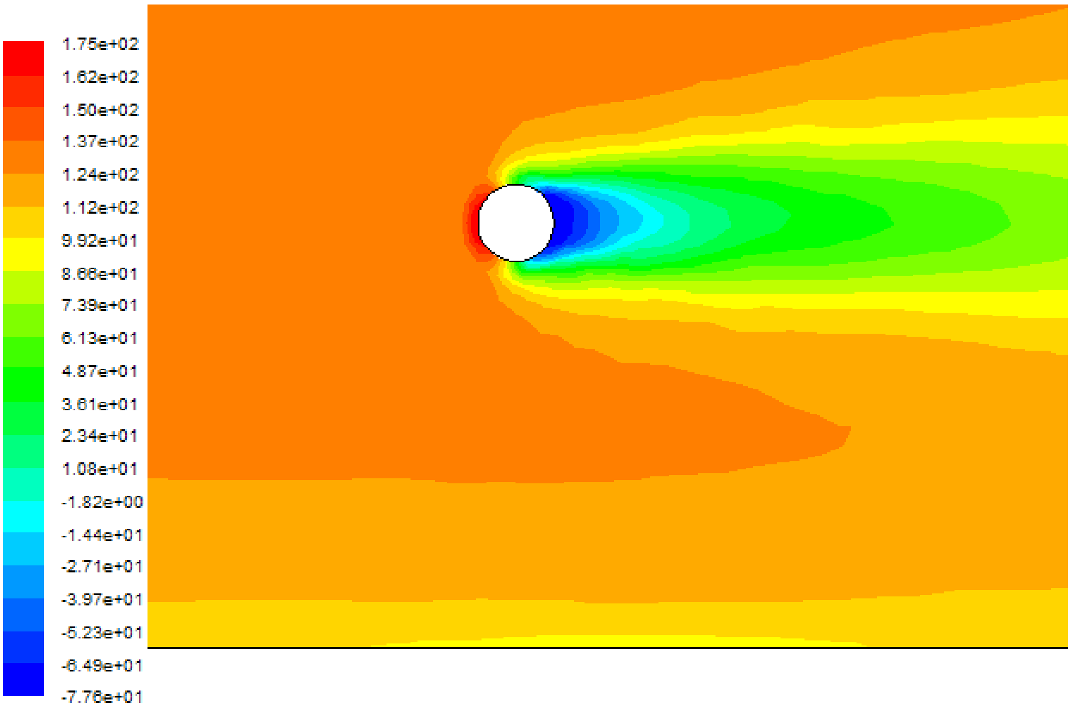

Figure 3.10 : Pressure distribution around the pipeline for 5D distance (Pa).

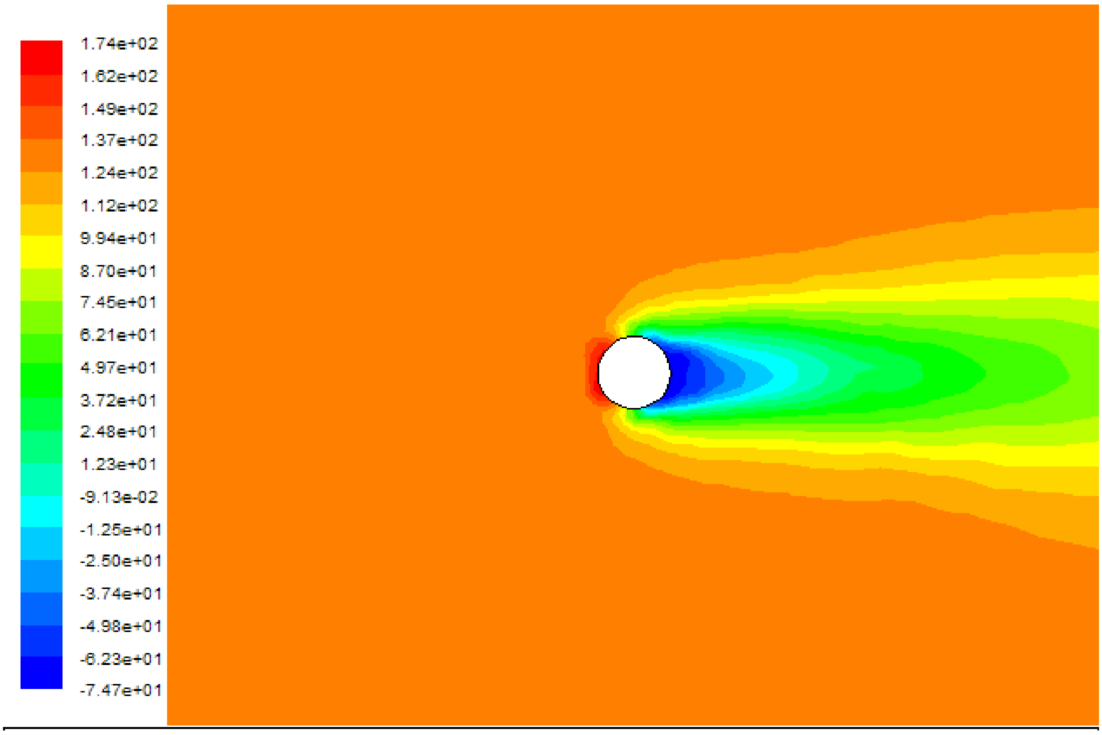

Figure 3.11 : Pressure distribution around the pipeline for 10D distance (Pa).

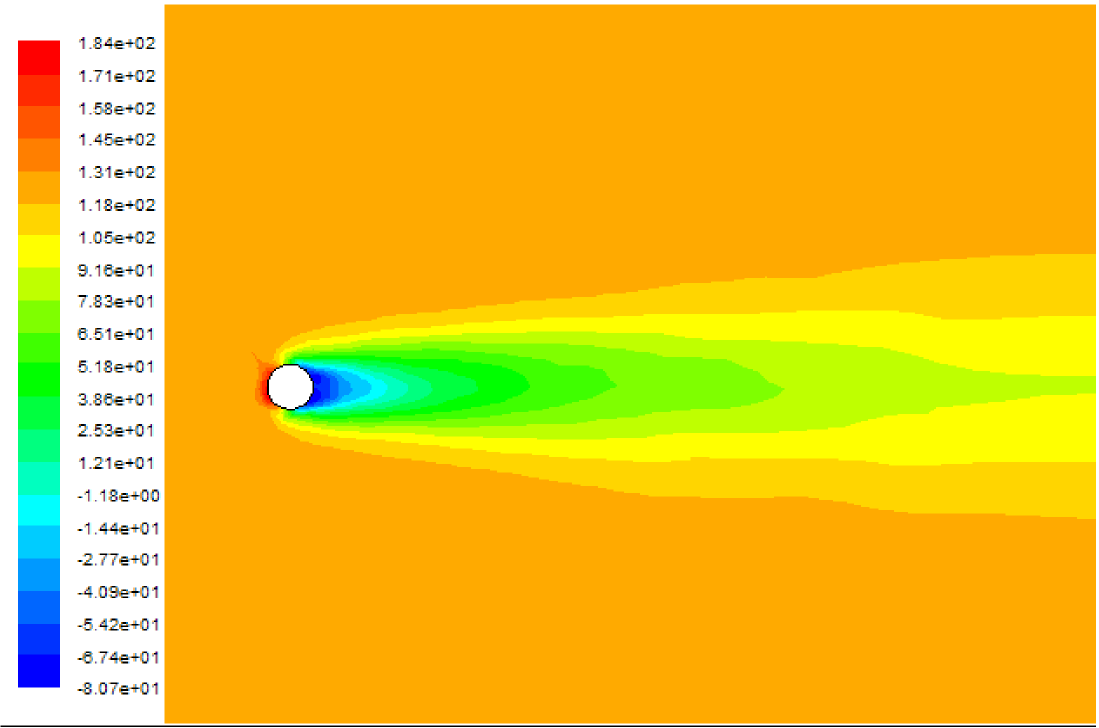

Figure 3.12 : Pressure distribution around the pipeline for 20D distance (Pa).

The relationship between the ratio of bed distance to diameter and Reynolds number is given in the following figure for a given velocity.

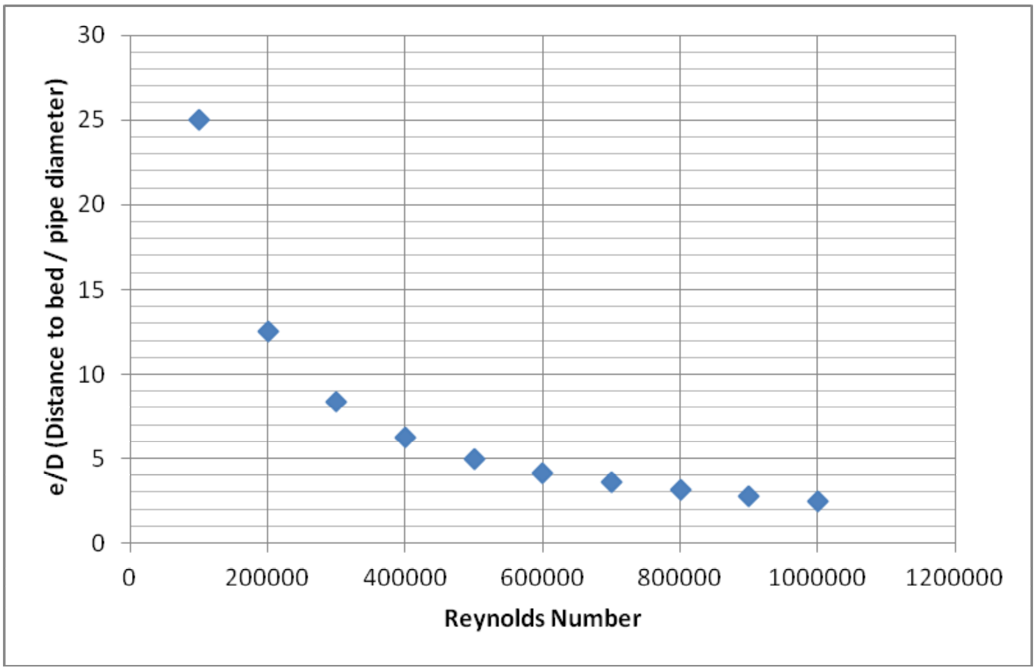

Figure 3.13 : Relationship between the bed distance and Re number (D=0.2,..,2 m)

The relationship between the force acting on the pipe and Reynolds number is given in Figure 3.14. As it is expected according to the equation 2.2, the acting force increases with increasing Reynolds number. The simulations are done for ten incremental velocity values.

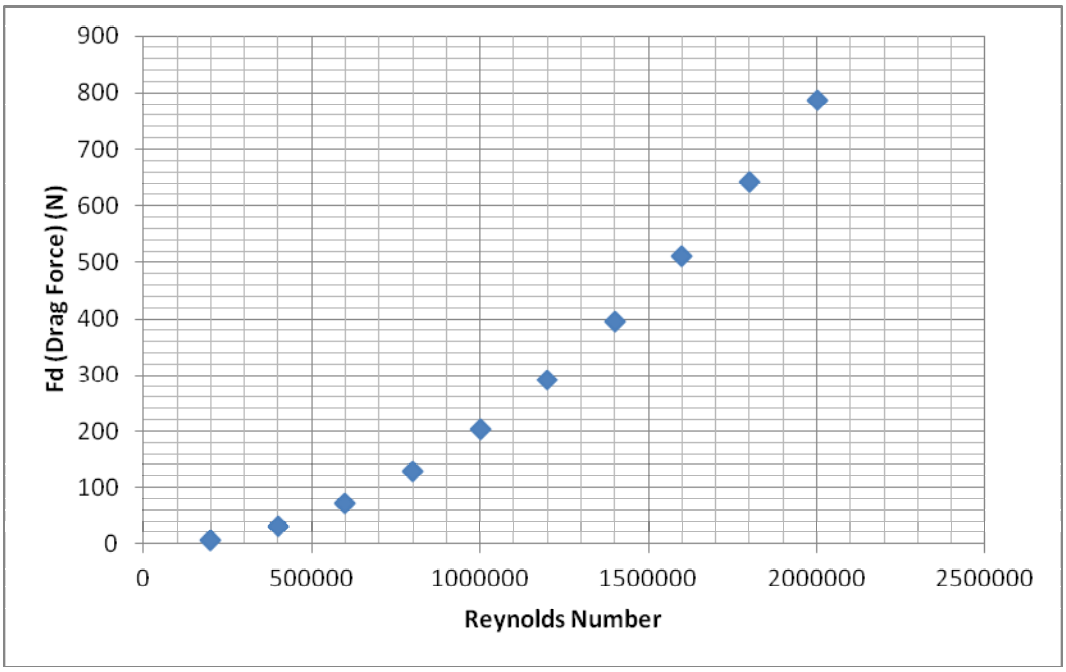

Figure 3.14 : Relationship between the drag force and Re number (V=0.1,..,1 m/s)

In addition drag coefficient parameter can be depicted from the forces obtained and shown in Figure 3.15.

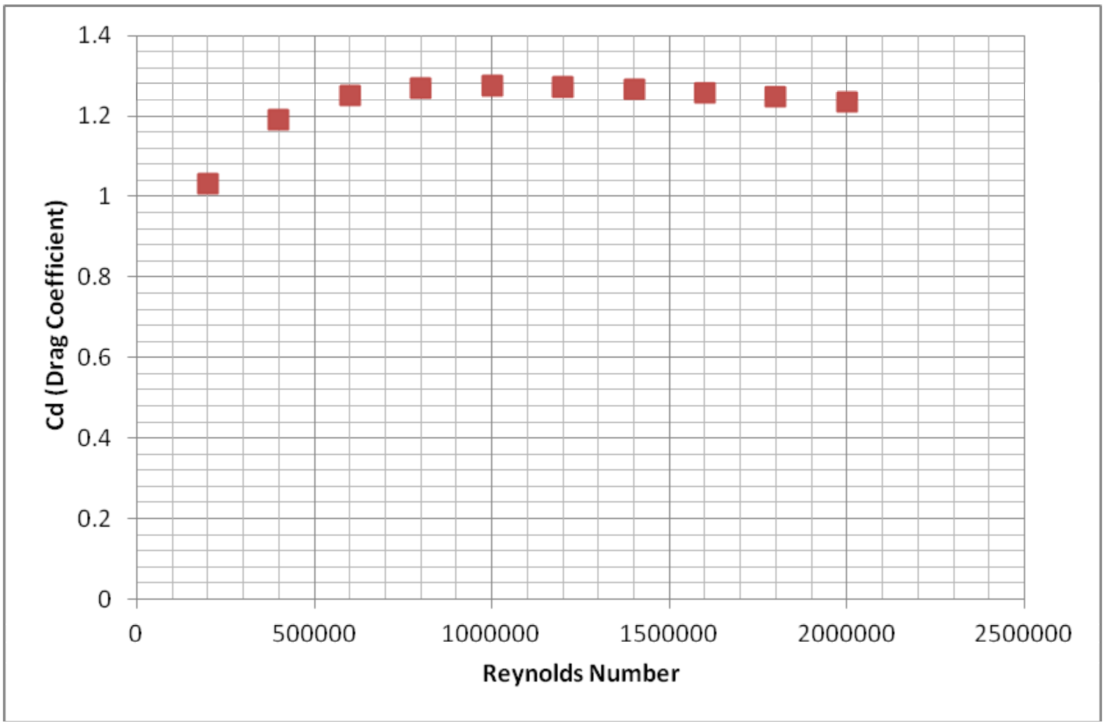

Figure 3.15 : Relationship between the drag coefficient and Reynolds number

The following figure shows the variation of drag coefficient with respect to the distance to the bed. It is seen that after obtaining a ratio of distance of 2.5-3.0, the drag coefficient tends to approach to a constant value, which would be the free stream value.

Figure 3.16 : Relationship between the distance and drag coefficient

3.4 Discussion of Results

Forces acting on a submerged pipe are analyzed by varying the pipe diameter, bed distance and deep water current velocity. Solved systems do not include buoyant or gravitational forces, because those forces are represented by distributed loads and differ according to pipe material, material transferred in the pipeline. Therefore, a static analysis should be carried out by considering the hydrodynamic forces mentioned in this study and other system forces depending on the design parameters. For flows having an angle of attack with respect to sea bed, superposition can be used as the pipe structure is symmetrical according to axial plane.

The span length, or the distance between the anchors should be also determined according to permissible deformation amount according to the material used.

The effect of distance to bed creates the most significant point to be considered during the design phase, which directly affects the vertical force acting on the pipeline that may increase/decrease the sag.

4. CONCLUSION AND RECOMMENDATIONS

The major purpose of this research was to demonstrate the effects of various factors regarding the design of an underwater pipeline system. The analyses are carried out by studying on a planar cross-section which successfully represents a unit length. The results obtained would help in specifying the layout of a pipeline system.

4.1 Application of The Work

In this thesis, some variables of underwater pipe lying are examined. In such a complex problem, a number of simplifications are made and steady-state results are demonstrated. As a future work, unsteady analysis can be thoroughly studied. Also, the axial forces and oscillations due to axial forces can be studied including the inner friction forces.

Debris flow is another issue to be addressed, both experimental and numerical studies should be carried out to correctly figure out the mechanism in moving bed conditions.

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