NATIONAL TECHNICAL UNIVERSITY OF ATHENS
M.Sc. of Marine Technology and Science
School of Naval Architecture and Marine Engineering

MSc Thesis

Modeling the distress of offshore high pressure pipelines due to earthquake deformations of the triggered slope instabilities and the consequent permanent deformations of the seabed

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Abstract

During the last years, the exploration of hydrocarbons has led to a great variety of energy projects internationally. More sustainable solutions are required now according to the legislations of environmental engineering. The industry interest is focused on new areas characterized by geopolital interest and great amount of hydrocarbons, not exploited yet. The academic interest tries to figure out the challenges and the hazards of those new areas, as the incoming projects will be occurred under different conditions. The economic benefit and the need of exploring news areas of oil and gas projects, turned into the wider area of Mediterranean which presents highly risked areas of seismicity.

The current Master thesis focuses on seismic events which can occur and provoke permanent ground displacements or deformations to offshore pipelines. For this purpose, a numerical modelling has been in order to calculate the distress of offshore pipelines due to landslide events triggered by seismic loads. The current study has been validated with an analytical solution suggested by academic researchers, and examines critical factors, such as the outside diameter and the length of landslide. The results are being compared in the end.

An extended literature review will show the challenges and factors involved in subsea and geotechnical engineering. It also includes different types of geohazards and mainly focuses on landslide events that may be caused by an earthquake. Interesting conclusions suggest alternative paths of further academic study.

Περίληψη

Τα τελευταία χρόνια, η έρευνα υδρογονανθράκων οδήγησε σε μια μεγάλη ποικιλία ενεργειακών έργων σε διεθνές επίπεδο. Πλέον απαιτούνται βιώσιμες και φιλικές προς το περιβάλλον λύσεις σύμφωνα με τα περιβαλλοντικά νομοθετικά πλαίσια. Το ενδιαφέρον επικεντρώνεται σε περιοχές που χαρακτηρίζονται από γεωπολιτικό ενδιαφέρον και μεγάλα αποθέματα υδρογονανθράκων, που δεν έχουν ακόμη αξιοποιηθεί. Το ακαδημαϊκό ενδιαφέρον προσπαθεί να εντοπίσει τις τεχνικές δυσκολίες και τους κινδύνους αυτών των νέων περιοχών, στις οποίες θα υλοποιηθούν τα έργα υπό διαφορετικές προϋπόθεσεις. Το οικονομικό όφελος και η ανάγκη διερεύνησης των νέων περιοχών με αποθέματα πετρελαίου και φυσικού αερίου εστιάζει σε νέα έργα στην ευρύτερη περιοχή της Μεσογείου, η οποία παρουσιάζει περιοχές υψηλής σεισμικότητας.

Η παρούσα μεταπτυχιακή εργασία επικεντρώνεται σε σεισμικά γεγονότα που μπορούν να συμβούν και να προκαλέσουν μόνιμες μετατοπίσεις ιζημάτων και συνεπακόλουθες παραμορφώσεις στους υποθαλάσσιους αγωγούς. Για το σκοπό αυτό, διεξήχθησαν αριθμητικές αναλύσεις για την προσομοίωση της καταπόνησης των υποθαλάσσιων αγωγών εξαιτίας κατολισθήσεων που προκλήθηκαν από στατικές και σεισμικές δονήσεις. Η τρέχουσα μελέτη έχει επιβεβαιωθεί με μια αναλυτική λύση της βιβλιογραφίας η οποία εξετάζει κρίσιμους παράγοντες, όπως η εξωτερική διάμετρος του αγωγού και το μήκος της κατολίσθησης. Τα αποτελέσματα που προκύπτουν από τις δύο μεθοδολογίες (αναλυτική και αριθμητική) συγκρίνονται στο τέλος.

Των αναλύσεων προηγείται μια εκτεταμένη βιβλιογραφική ανασκόπηση, η οποία περιγράφει τις προκλήσεις και τους παράγοντες που εμπλέκονται στην υποθαλάσσια γεωτεχνική μηχανική. Περιλαμβάνει επίσης διάφορους τύπους γεωκινδύνων και επικεντρώνεται κυρίως σε φαινόμενα κατολισθήσεων που μπορεί να προκληθούν από σεισμό. Τα συμπεράσματα αποτελούν τη βάση για προτάσεις περαιτέρω έρευνας.

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1. Introduction

From the academic view, offshore pipelines have an attractive importance as it is a modern and really multi-discipline topic with a lot of aspects that require further consideration. Lots of major offshore pipeline projects are established in areas of low seismicity, so we have not seen any great damages to offshore pipelines and structures related to seismic events.

However, recent researches have focused on Mediterranean Sea and Middle East gas fields. The large amounts of gas fields and the need of transportation of hydrocarbons from those two regions to central and north Europe attracted the interest of oil and gas industry and there lot of prestigious projects reaching on there in the future. At the same time, the continuous activities for the last twenty years in North Sea are now stopped and the oil prices are cutting down day by day so the industry turns into different ways for the future projects. Those various parameters are the motivation of this current study which tries to highlight the issue of pipeline distress due to subsea landslides.

1.1. Technical background and research idea

During the last years, the interest of exploration of hydrocarbons has increased a lot in order to secure energy solutions internationally. At the same time, the academic research regarding ways to explore energy resources became stronger as the geopolitical interest and the agreements between different countries tend to strengthen the importance of accurate methods of installation of offshore structures. The economic benefit of those projects is another important motivation for the industry to eliminate the damages of those structures.

Because of the increasing interest, recent projects are now considered for depths of 1000 m which reach to depths of 2000 m in contrast with past projects which were considered for depths of 100-200 m. In those cases, upstream analysis for ultra-deep water requires advanced offshore geotechnical engineering which is a very challenging procedure.

Analytical solutions of those energy projects should take into consideration how we can evaluate the feasibility of offshore structures: an issue which is related on geohazards. The term ''geohazards'' includes all the geological phenomena and processes which have the potential to produce accidental events or failures to structures that can cause loss of life to them. As it is shown in Figure 1.1, examples of geohazards include slope failures, active faults, adverse soil conditions, landslides, over-pressure strata, etc. All these geohazards may be triggered by external events, such as earthquakes, storms or humans' activities. Especially the following structures seem to have a great impact from geological phenomena and require a detailed analysis for the installation and the operation:

- Exploration drilling rigs
- Subsea pipelines, cables and manifolds
- Foundation of steel jacket production platforms
- Jack-up platform foundations
- Concrete gravity base structure
  - Risers and anchors for subsea mooring systems in upstream water

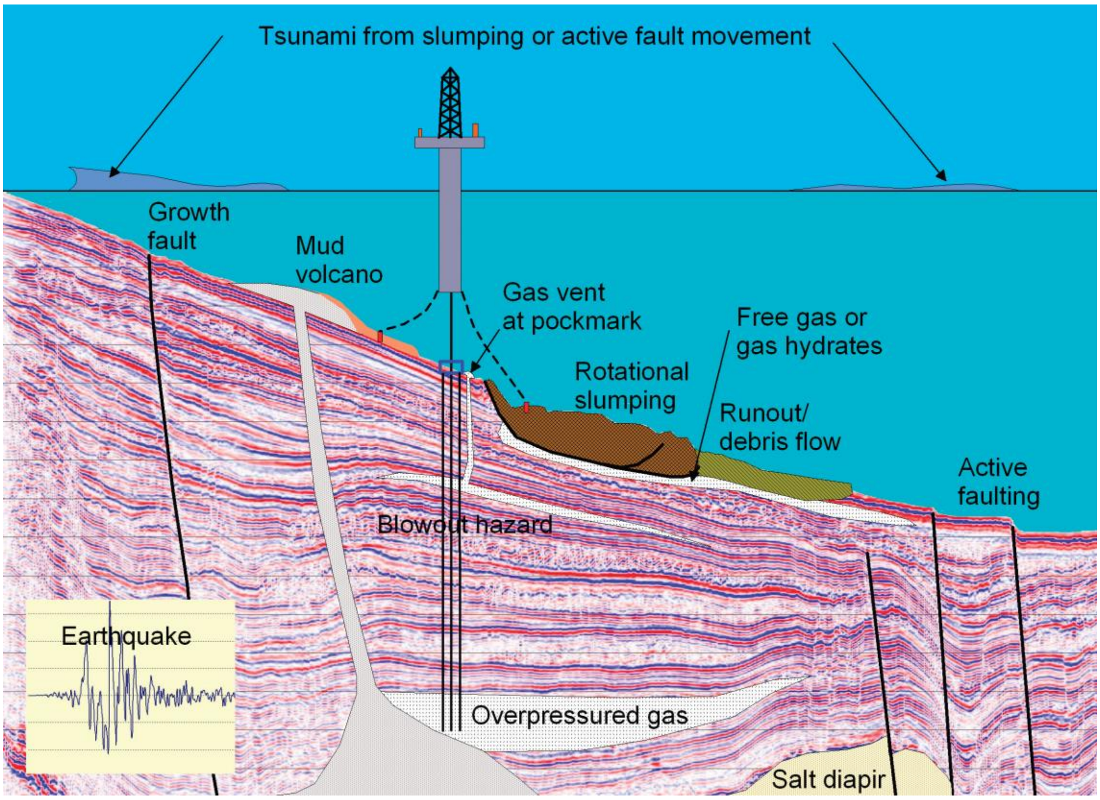

Figure 1.1 Offshore geohazards [Parker et al., 2015]

At this part, we should emphasize that designing in an offshore environment taking into account geohazards is a really fascinating issue which is actually one of the most progressing research aspects of marine geology. What we try to do is to estimate the damages of each geohazard and how we can eliminate its impact to the structure under consideration in order to keep the structure safe and serviceable. Given the difficulties and the variety of disciplines involved in that issue, lots of specialists from technical background (geologists, geophysists, geotechnical engineers, subsea engineers and numerical modelers) try to figure out how to calculate quantitatively the risk taken. Under this perspective, the following steps are required:

1. Collection of all available information regarding the seabed and subsoil interaction with the structure
2. Identification of the specific location of geohazards
3. Calculation of the activity and the magnitude of those events

Simply, the solution of this complex problem is described in the following equation:

$$Risk=Consequence\times Hazard\times Vulnerabiliy \quad (1.1)$$

Hazard is characterized as the probability of an accidental event to be occurred, while the consequence describes the total damage caused by the event. All these consequences may mean a great variety of damages into structures and this assumption comes into terms of financial engineering. In the case of geohazards, things should be more complicated and the previous assumptions must be made from a specialist team of scientists to succeed in this process.

On the other hand, we should mention that there are two different types of geohazards. The first category includes the geohazards can cause damages to a structure during the installation procedure in contrast to the second category which refers to the geohazards that can cause damages during the operating life. This is due to the fact that oil companies and contractors care a lot about the installations damages in contrast to the countries and governments which care about operating damages.

Offshore pipeline engineering is a relatively new topic which seems to be very challenging for those who are involved in oil and gas industry. Pipelines are preferred when onshore solutions are not allowed in order to transfer the hydrocarbons to points where can be sold and produced. Those distances and the cost of them is a great issue for the specialist engineers to select the optimum route to eliminate technical damages but also a great issue for oil companies, contractors and generally for the countries, in which the fuels transfer, to reduce the cost.

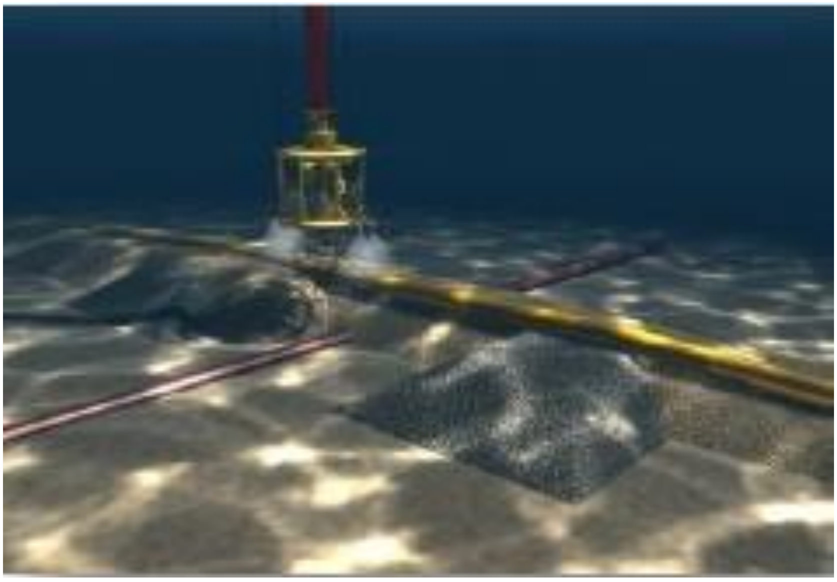

Figure 1.2 Offshore pipeline after installation [www.yourindustrynews.com]

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The question is what is going on now with the expected activity of offshore facilities and installations in those areas. The literature covers the majority of those problems in onshore environment and many design methods are based on them. In reality, offshore environment is more complicated than that. Additionally, we have another difficulty: recordings of ground motions in an offshore environment are surprisingly rare so in the analyses we are based on recordings of onshore seismic events. As a result, the seismic response of offshore pipelines is so challenging nowadays as we even do not be sure about the input motions to resolve that challenging problem. Moreover, the influence of seawater depth changes the saturation and the pore pressure of subsea soil layers and all these parameters increase the difficulty of the problem.

The geological profile in ocean seabed is not always the same and consists of different types of clays that may vary from a few to hundreds of meters. All these different categories of soils mean that earthquake loads and forces may provoke a different behavior of the seabed in each case. As a result, predicting the behavior of a long pipeline crossing lot of kilometers of different soil formations is a complicated issue and requires special attention to various parameters.

We should mention that before using numerical and analytical solution to calculate the deformations of the seabed, it is beneficial to talk about all the issues involved in the assessment of earthquake geohazards and the seismic response of oil and gas infrastructures. We will present the role and influence of geology, bathymetry and seismicity which describes the areas of Mediterranean and Middle East in order to make this project appropriate and applicable to those areas, which is the main aim of the current thesis.

1.2. Motivation study and objectives

Given our interest and the hope for future projects in the Mediterranean Sea, we decided to focus on the seismic response and distress of offshore pipelines due to earthquake triggered slope instabilities, as seismicity is one of the greatest problems of the wider area. The aim of the current thesis is to examine a way to calculate the permanent deformations under those seismic loads which can lead to landslide loading. This can be cause an area of free spanning which would have an impact to the operation of the whole structure and this study tries to discriminate different loadings and their consequences to this free spanning area. The Figures 1.3-1.6 indicate the pipeline routes in Mediterranean and also the highly risky areas of seismicity.

Figure 1.3 Natural gas pipelines in Europe[Samaras,2012]

All these factors are only some cases of the total ones that can effect and damage an offshore pipeline during its operational lifetime. We are interested in working in a complicated and greatly new topic which may be interesting in Mediterranean and Middle East, new areas that have not yet experienced the activities and facilities of offshore industry. Taking into account all those designing parameters, this study is itself a really challenging procedure as literature could not help us totally in our academic research.

Also, historical evets have never faced problems related on seismic events as all the projects were installed in areas of low seismicity. So, this study is helpful as a first step of valuation the deformations caused by active landslide in an offshore pipeline. For this purpose, finding an academic research which is mathematically difficult could not be appropriate for the current objective.

Figure 1.4 Highly risky areas of seismicity in Mediterranean [Vanucci et al, 2004]

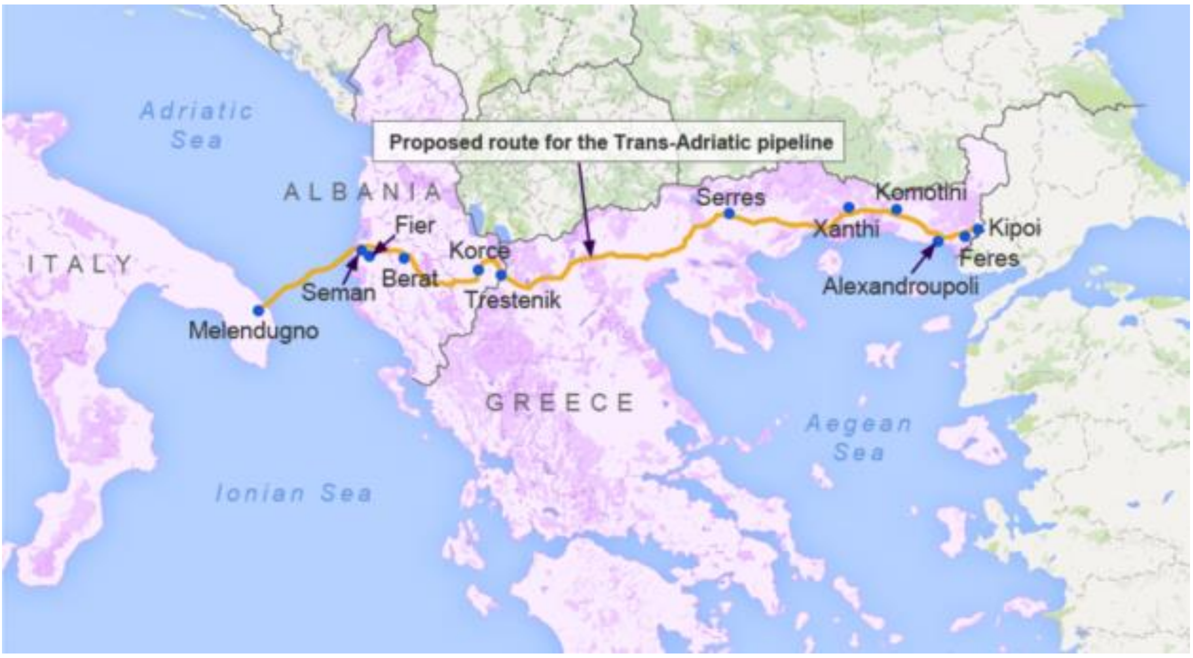


Figure 1.5 Pipeline route of Trans Adriatic project [www.voanews.com/a/european-energy-security]

As the real offshore environment is so complicated, the real challenge was to develop a simplified, but realistic, solution. The following parameters should be idealized: soil-pipe interaction, geometry of the pipe, inclination of the seabed, active loading of landslide. Lots of scientists tried to predict this behaviour using dynamic models which make the solution more demanding.

The main purpose of this study is to develop a finite-element model of the pipeline, and its connection to elasto-plastic springs under the different types of the seabed. Loading conditions caused by seismic loads will be applied into the model using ANSYS. Based on the calculated seismic loads, the assessment will be extended to determine the displacements of each case having different widths of landslides, different loading conditions and geometrical characteristics of pipelines (e.g. pipe diameter).

Under those circumstances, we will try to enlighten the difficult and complex problem of a pipeline under seismic loading and how we can identify the behavior of the pipeline while landslide impacting on it in a linear way. The results will be analyzed with analytical and numerical methods in order to be compared later and get the validation accomplished. The problem is focused on the free span area of the pipe and the calculations will be verified by analytical solution. The software used is ANSYS, which is appropriate for the simulation of soil-structure interaction problems.

Figure 1.6 Proposed route of East Med Pipeline project [https://energypress.gr]

2. Offshore Pipelines

The current chapter tries to emphasize the challenges in the design and construction process of offshore pipelines. It includes the different type of forces acting on the pipeline and different categories of installation. Also, it highlights the importance of seismicity of offshore pipeline facilities and why we should take care of it for future projects, especially in the wider Mediterranean area.

2.1. Designing parameters of offshore pipelines

Offshore pipelines in a general term are long structures which transports different types of fluids (e.g. hydrocarbons, water) at the same time. The parts, which consist of and their connections are more complicated than that. As shown in figure 2.1, offshore pipelines are used:

- From wells to manifolds
- From manifolds to platforms
- Between platforms
- From platforms to shore terminals
- From platforms to wells
- From land terminal to land terminals, by crossing oceans

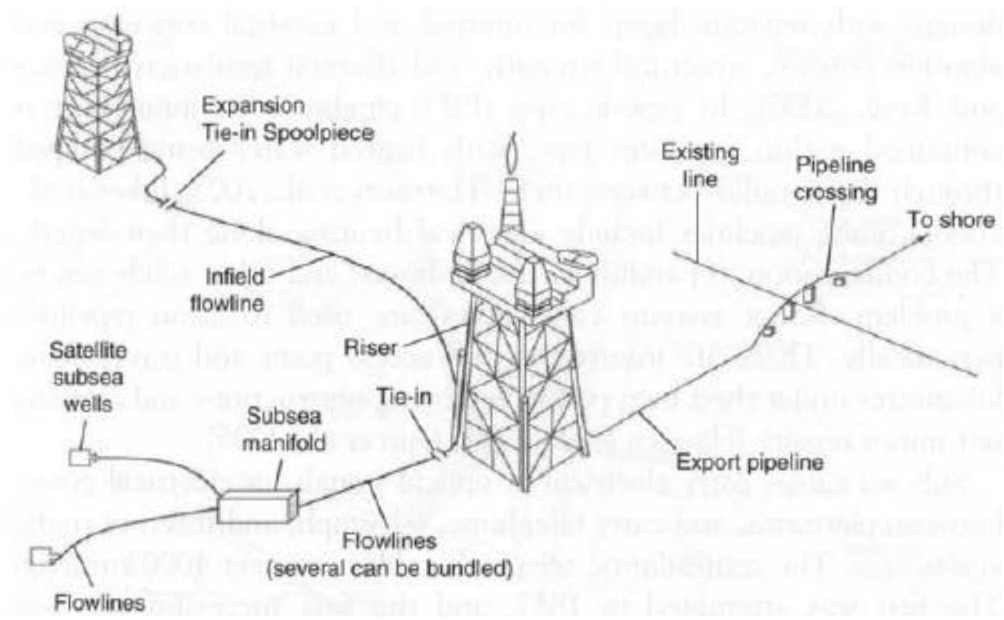


Figure 2.1 Infield and export flowlines [Dean, 2010]

2.2. Designing parameters: static and dynamic forces

An offshore pipeline should be strong enough to resist into different types of loads during construction. During this phase, it will be loaded by internal pressure from the fluid carrying on, external pressure by the sea, the waves and the currents and by stresses caused by temperature changes. There are the following categories of loads which can provoke damages to offshore pipelines:

1. Functional loads: All these loads are action resulting of the operation of the pipeline. Examples of this category are:
    - Internal static pressure
    - Pressure surge
    - Operational temperature

2. Environmental loads: This category consists of the loads provoked from the natural environment. Examples of this category are:
    - Hydrostatic pressure
    - Buoyancy
    - Self-weight
    - Wave loads
    - Soil pressure
3. Accidental loads: The potential loads can be provoked into natural hazards or any other events may damage the pipelines. Some cases of this category are:
    - Dredging areas
    - Shipwrecks
    - Fishing activities
    - Military activities
4. Installation loads: This category include all the other types of loads can be occurred in the installation method. For example, loads from installation testing can also damage the pipeline if designing analysis is not accurate and detailed.

The Figure 2.2 shows the categories of forces applied in an offshore pipeline, as described above.

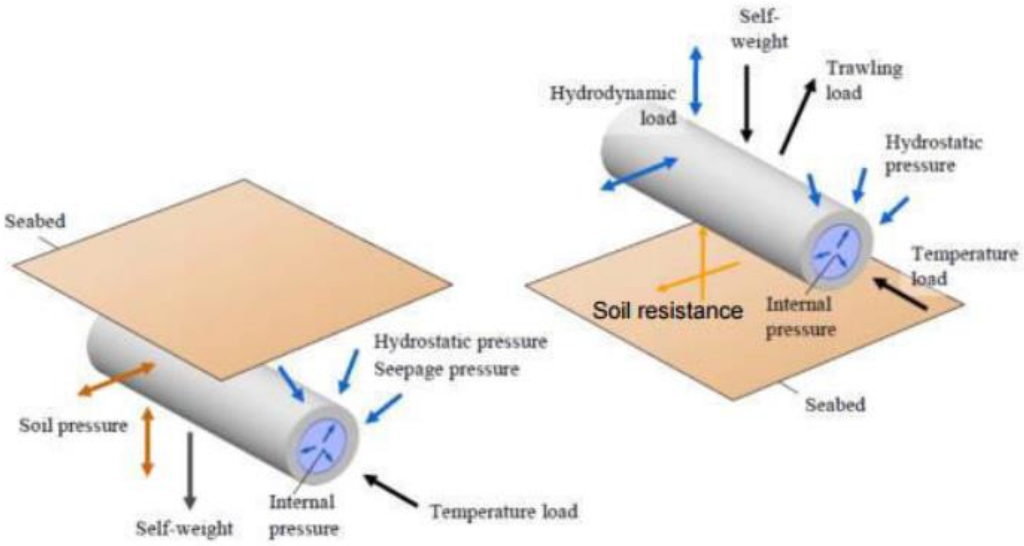


Figure 2.2 Forces in offshore pipelines [Khorasanchi,2014]

There exist a variety of parameters involved in the design and analysis of offshore pipelines. The diameters, the length, the wall thickness, the materials and the manufacturing process are some of the important ones. Those can be identified by extended static analysis while calculating the characteristics of the structures and the loads can resist under accidental events. The stability on the seabed or the thermal expansion of the pipe and the accuracy of the multi-phase flow are some other topics related to the design. Those issues require more detailed analysis and the cooperation of specialists of different disciplines in order to achieve the optimum solutions-decisions.

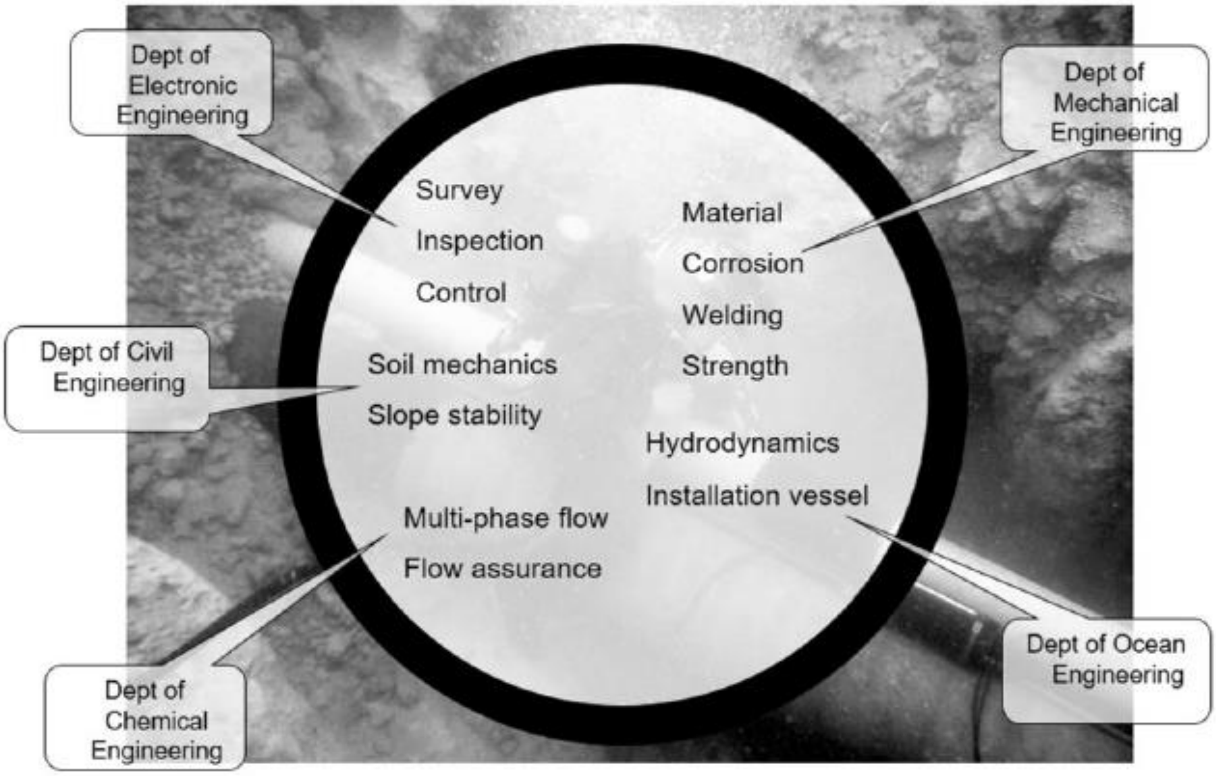


Figure 2.3 Different disciplines involved in Offshore Pipeline Engineering, [Khorasanchi, 2014]

2.3. Seismic loads: key factor of design

Pipeline should have sufficient resistance to internal and external pressures, and should be insured that will not buckle and must be stable in the seabed. The design issues that should be taken into consideration are the following:

- Temperature (internal and external)
- Pressure (internal and external)
- Routing
- Corrosion

- Hydraulics
- Flow assurance
- Strength
- Stability on the terrain

Increasing lengths of the pipelines into deeper water means that during the last decades the design and installation of pipelines into an offshore environment is more demanding than before. Obviously, the repair procedure to pipelines is extremely expensive as the access into offshore environment is not that easy as in onshore pipelines. That means that the operation of the structure may be interrupted and the cost of the construction works for the oil & gas companies may be high. Those two concepts are the main guides when the oil & gas companies decide the method of installation and try to eliminate any other damages during the lifetime of a pipeline.

One of the most challenging cases is the stability on the seabed which can change under accidental, environmental loads into the structure. Actually, those loads are so important for the route selection especially if they are related on seismic events. In the route selection, apart from the distance to the shore, construction limitations and other environmental or geopolitical considerations, where are constants from the installation period, we should take care the seismic loads which can damage the pipeline during its operational lifetime.

2.4. Challenges in the installation process

The success of installation depends on the good understanding of the dynamics of marine structures. All these procedures, in order to be applied, should have been validated by methods and simulations based on analytical and numerical models, given that eliminating errors is necessary for those structures. We will indicate the different types of installation method and point out the challenges of each method.

2.4.1. Modelling of pipeline

As it was aforementioned, the use of subsea pipelines means a safe and environmentally friendly solution for the transportation of hydrocarbons. Of course, the size of diameter, the exact area where the installation will be occurred (shore or deep water) define the method and the difficulty of the whole process. Currently, the needs of offshore industry to apply offshore pipelines into deeper waters mean that the variety of hazards will be increased. Hence, pipeline technology concerns about installation of large depths projects and in particular the large gas gathering and distribution systems, just like in Gulf of Mexico, North Sea.

Figure 2.4 shows a pipeline installation from a surface vessel. The main purpose of this method, called *pipelay operation*, is to position an elastic pipeline into a specific path of the seabed only by means of the active control of the pipelay vessel position, while ensuring the structural integrity of the pipe.

For the detailed analysis of offshore pipeline projects, we should take into account which mathematical models are needed to determine pipe properties, pipelay parameters and the safe conditions of the installation. Hence, dynamic models were based on elastic beam models as known from continuum mechanics.

Figure 2.4 Offshore pipe laying operation [Stenberg, 2009]

2.4.2. Modelling requirements

While modelling the pipeline, a variety of requirements may be taken into consideration. The following parameters describe the success of the modeling process:

- Real- time computation: The model should be simple enough to compute in real-time conditions.

- Dynamic: The model must capture the main dynamic forces of the pipe.
- Accuracy: The computation should be sufficient for the application.
- *Stability:* The closed-loop system should be stable, which means that accidental, environmental or any other types of loads have taken into account in the design.

2.4.3. Construction Methods

The installation of pipelines and flowlines and their connections to platforms are described as one of the most challenging stages of offshore technology. Therefore, the cost and the size of the installation may differ depending on the needs of the project.

Briefly, we may refer the basic methods of installation, as they are defined in pipeline installation technology. There are three main categories of installation, each of them needs the appropriate equipment and technical background:

1. S-Lay
2. J-Lay
3. Reeling

The key concept of all these methods is to keep the pipe under tension in order to maintain bending and axial stresses in an acceptable range. Through continually controlling the tension of the pipeline being laid, excessive of bending is avoided without the necessity of support structures or any other buoyant parts, which is applicable to shallow waters.

We could mention that S-Jay method is used for shallow waters, instead of J-Lay method which is more suitable for deep waters. However, the term of depth is not specifically defined given that the installation technology changes day to day the installation methods regarding industry needs. Hence, the range of depths in each category increases as the new projects are referred to deeper waters.

The terminology used in subsea and pipeline engineering sector divides the waters into: shallow, intermediate and ultra-deep category. Depending the installation method, the cost and the depth of each project, the length of the pipe varies from 1-1.5 km for the S-Jay method, and 5-6 km for the J-Lay method. For the reeling method, the average rate is 15 kilometers per day. We would like to clarify that all these methods need the appropriate equipment and fitted vessels, only a few companies can provide that.

S-Jay method

S-Jay method is the most common method of installation. As shown in Figure 2.5 Large numbers of pipe joints are coated and manufactured onshore. The pipelay joints are brought to the vessel so the construction cannot be interrupted. Onshore the vessel, the pipe joints are welded on to the end of the pipeline in a horizontal direction called *firing line.* The pipeline is held in place to facilitate construction by so-called *tensioners*, which press the pipeline going down to the seabed. When the pipe has been extended with the new pipe joints, the tensioners control the speed of the vessel, while maintaining the tension of the pipe.

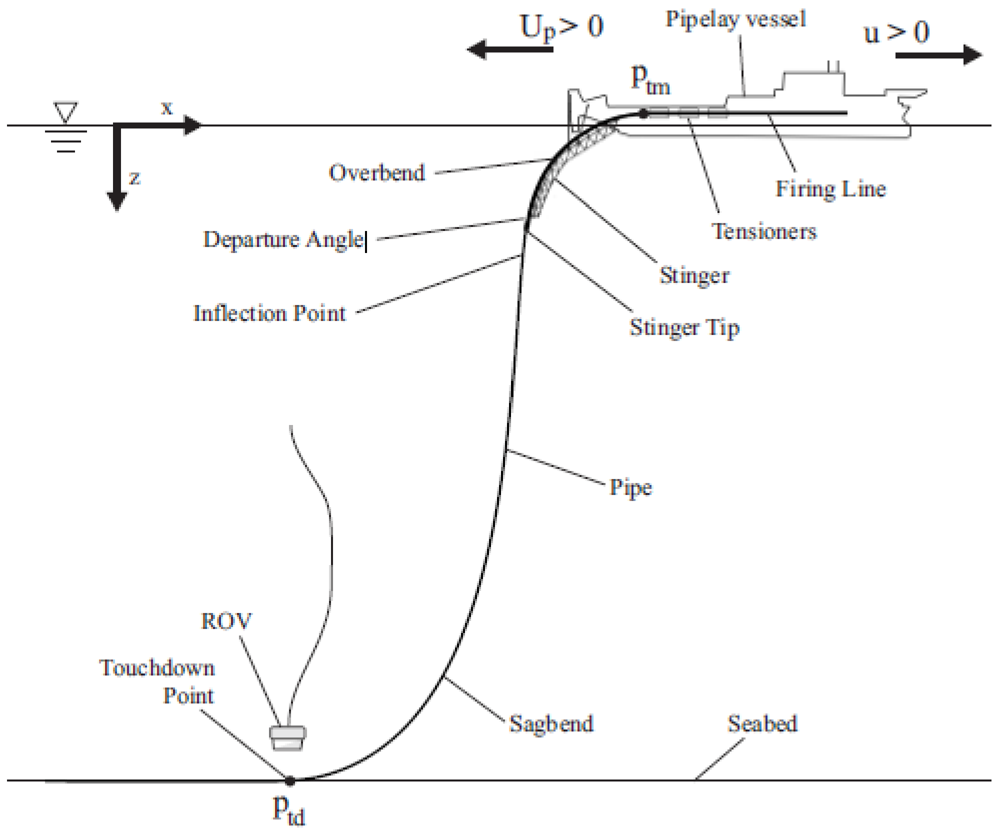


Figure 2.5 Construction process of S-Jay method [Jensen, 2010]

The main advantage of this method is the long firing line helps the parallel workstations for assembly of pipe joints, so four pipe joints can be added at the same time. As a result, this method is characterized faster and economical, especially for the long pipeline projects. Although this method is fast, the pipe should be supported to a vertical departure angle and the power needed to resist the tension increases a lot while trying to install a pipe into deep waters. This means that this method presents great disadvantages into deep waters installation.

Typically, the lift off angle will be in the order of 30° for a project of 100 meters depth. While the depth increasing, this angle will be up to 90° and if the tension is still kept, that would be within practical limits. This is commonly known as Steep S-Lay method, which can be applied by specific vessels, like the Solitaire.

J-Lay method

In deeper water conditions, the catenary configuration of the pipeline from the seabed to the pipelay vessel is near vertical at the pipelay vessel end. Based on this configuration the method called J-Lay, as the pipe leaves the vessel in a nearly vertical position and the pipe resembles to letter J. The pipeline is constructed in a vertical ramp which consists of tensioners and workstations.

The ramp angle is adjusted so that it is in the line with the pipe catenary to the seabed. This way bending to a pipe becomes minimum. The great advantage of this method is to reduce bending risks, which is very important while installation of pipelines that are sensitive to fatigue. Furthermore, this method has a low production rate due to the single position welding of the pipe.

Figure 2.6 Saipem 7000 owned by Saipem, has been in operation since 1998. [Jensen, 2010]

Reeling method

One of the most efficient methods is the Reel Lay Method, which is suitable for the installation of cables, flexible pipes and umbilicals, all these structures that have small diameter. The pipe is constructed onshore in a controlled factory environment and spooled onto a large diameter reel fitted on the vessel. The loaded vessel then travels to the installation area where the pipe is installed by unspooling as the vessel moves. Then, the pipe straightens and lowers to the seabed.

The major advantage of this method is the total control of welding and inspection, as those procedures are applied onshore. Also, this method has a high production rate.

Figure 2.7 400 mt Reel-Lay System Seven Ocean, Subsea 7 [Jensen, 2010]

2.5. Offshore pipeline projects in the Mediterranean Sea

As we have already clarified, lots of big projects related to offshore pipeline industry have been applied in areas of low seismicity. In the early of 1970's, when the subsea technology started continuous activities, the main oil-productive countries were Norway, United Kingdom, and Mexico.

The image in the international market seems to be different, as the downturn in oil and gas sector has continued during the last years. All the countries try to discover their fields of hydrocarbons in order to reduce the cost of transportation route and provide a dynamic economy into their own nation. Under those circumstances, future projects and recent ones are focused on the wider area of Mediterranean, a new area of exploration which hides lots of risks and challenges.

2.5.1. The Trans Adriatic Pipeline Project

That project will carry the Caspian natural gas to Europe. It is a highly promising project, as it connects the south countries via 878 km length route . The TAP, as it is called, has a great value in energy market because it will totally change the relations between the south energy markets.

As it is shown in Figure 2.7, it starts from the Greek-Turkish borders, crosses the north part of Greece and whole Albania, and finally ends up to Italy. That means that this project has an extra challenge: 105 km of the length will be installed in offshore environment, crossing the Adriatic Sea.

It is regarded as one of the most important projects that will keep the energy security between Italy, Greece and Albania and of course connects the Caspian fields into European markets and hopefully this route selection will reduce the oil and gas prices into south countries. The offshore part of the pipeline will be constructed in 2017-2018 and as it is scheduled, in 2019 all the construction works will have been finished. The operation of the pipeline is expected to start in 2020.

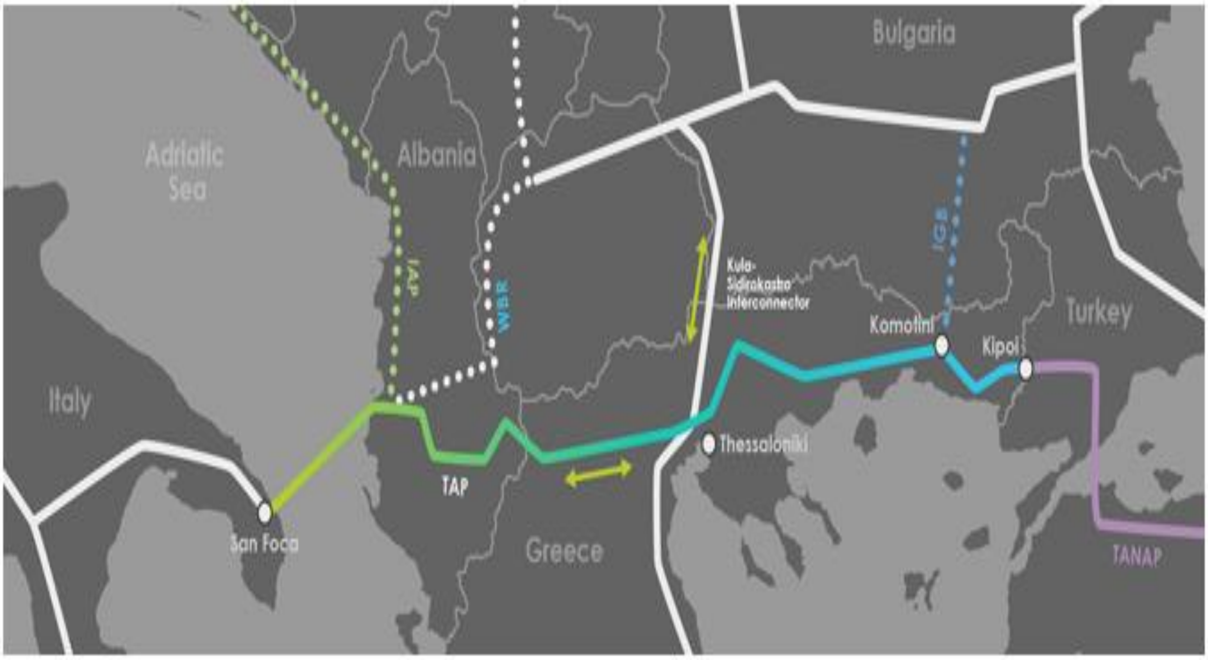


Figure 2.8 Route of TAP project [https://www.tap-ag.com/the-pipeline]

2.5.2 East Med Pipeline Project

Undoubtedly, this project attracted our attention for political and economic reasons. This future project really gives the impression that Mediterranean and Middle East can combine their knowledge and technical background and co-operate for a prestigious project in the wider area. The benefits will be great in the economy of all involved countries, namely Israel, Cyprus, Greece and Italy.

The proposed 2,000 km subsea pipeline would connect gas fields of Cyprus and Israel with Greece and hopefully with Italy. Many popular and prestigious oil contractors are interested in that project, such as Exxon Mobil, ENI, KOGAS, Novatek. The detailed navigation of the area indicated that the fields of gas are significant.

That project seems to be really ambitious and it is at an initial phase, as the agreement between Israel and Cyprus has just signed. For political and financial issues, we hope the exploration will start in 2025, as agreed.

Figure 2.9 Route selection of East Med Pipeline Project [Samaras, 2012]

3. Offshore Geohazards

This chapter starts with the definition of the term 'geohazards" and describes all the categories of geohazards in order to understand their importance for the oil and gas projects. Also, this chapter focuses on earthquake related geohazards and especially on the triggering mechanisms of landslides, which is the purpose of the current thesis.

3.1 Definition and categories

Geohazards are all the hazards related to the geological or geotechnical issues or processes that may provoke damages to integrity or serviceability to structures or to their foundations during design lifetime. For offshore oil and gas structures, geohazards may cause injury or loss of life, damage of the environmental infrastructure. All these cases may cause additional project costs. The figure below can show the variety of geohazards, such as landslides, disturbed sediments, unconsolidated soils etc..

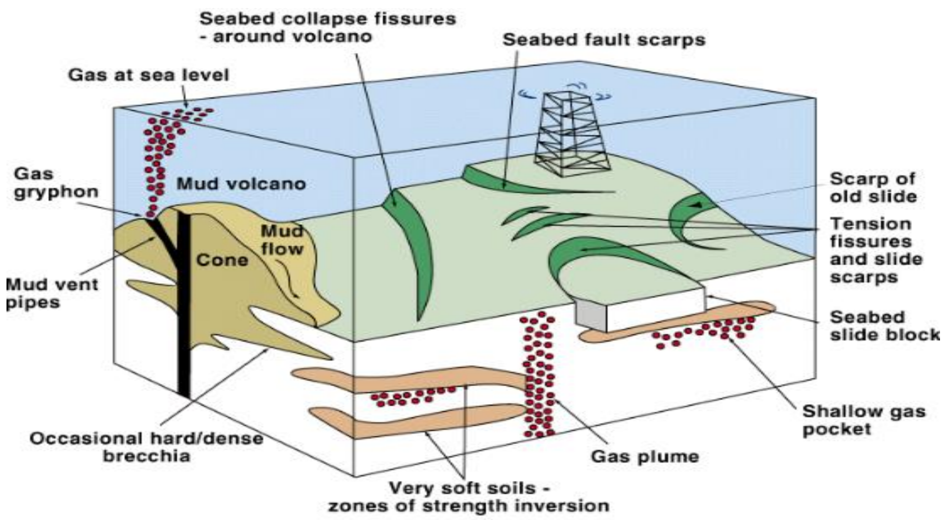


Figure 3.1 Different types of geohazards [Power et al., 2005]

Figure 3.2 depicts all the categories of offshore geohazards observed in deep waters. In the current thesis, we take into consideration the case of deep waters, since our interest focuses on applications and activities in the wider area of Mediterranean Sea, where the water depths are substantial. Also, geohazards are more significant to deeper waters so the damages will be greater into an accidental event.

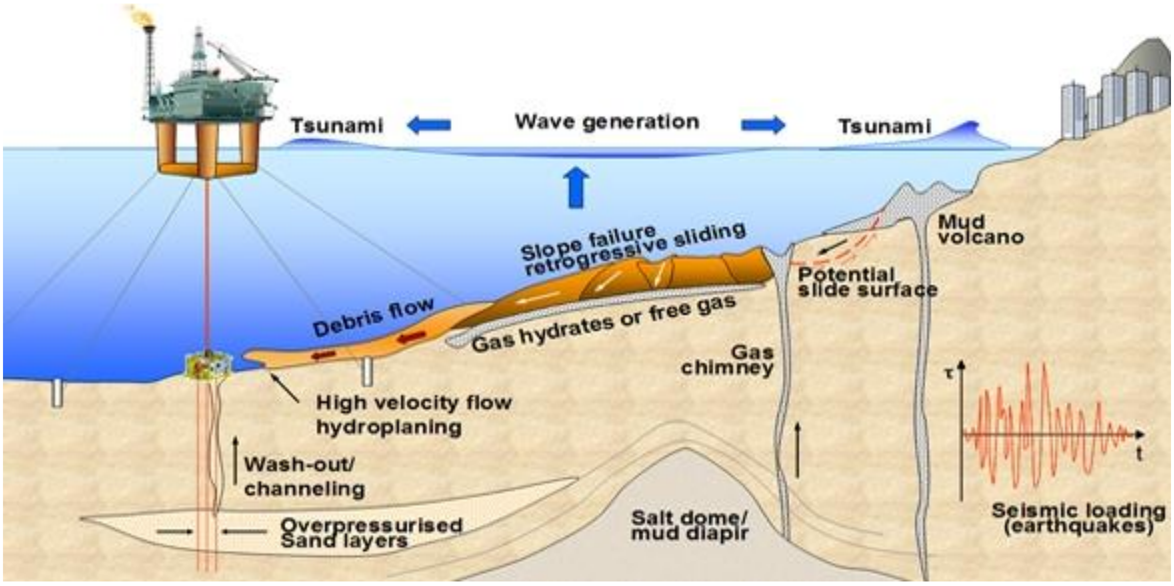


Figure 3.2 Offshore geohazards [Strout and Tjelta,2007]

Geohazards are divided in two main categories:

1. Hazardous events: Events those are infrequent and episodic in nature. Examples of this category are: earthquake events, tsunamis, submarine slope movements and gas expulsions.

2. Hazardous ground conditions: Conditions that provoke damages in slow process, such as soil-creep, non-tectonic soil creep, mud or salt tectonics.

The risk related on geohazards depends on:

- Frequency of the occurrence
- Severity of the event
- Location of geohazard and the distance from the subsea structure

So, all these parameters affect the results and the deformations in the structure. Therefore, it is not only necessary to apply deterministic models of failure of the events, but taking into account the probability of failure events occurring during the design lifetime of the structure.

The topic of geohazards, as it was mentioned before, is so complex and multi-parametric that we cannot analyze in detail all involved issues and parameters. In the current thesis, we emphasize on slope failures and slides as mass movements that can have catastrophic results to offshore pipelines. We will focus on that aspect of geoharard and describe briefly the whole process of avoiding geohazards.

3.2. Risk Assessment of offshore geohazards

The first challenge of the geo-scientists is to assess the risk of the geohazard. Briefly, we remind the equation of the introduction, which gives a simple solution of this complex problem of geohazards.

$$Risk = Consequence \times Hazard \qquad (1)$$

In this equation, geoscientists have to figure out how to quantify the the geohazard, which means the location, the frequency and the magnitude of the event. Additionally, they need to identify the consequences of the event which describes the evaluation of the impact of the geohazard on the structure.

The assessment of the risk requires geohazard identification, failure scenarios and related results of the event. Geohazard identification examines the evaluation of existing conditions and stability of subsea structures. Also, examines the possibility of stable conditions to be transformed to unstable ones. Failure scenarios can be natural, such as earthquake, tectonic faulting, temperature increased by climate change, excess pore pressure due to rapid sedimentation and gas melting caused by increased sea water temperature, or man-made, such as rock filling for pipeline supports, forces from ships and platforms.

Evaluation of the slope stability, soil shear strength and earthquake load effects are only some of the results that may be provoked from geohazards. The main idea is to define the identification of geohazard and the probability of occurrence. In the figure below, we could see a plan of the whole procedure in order to understand how it scientists examine the risk estimation step by step.

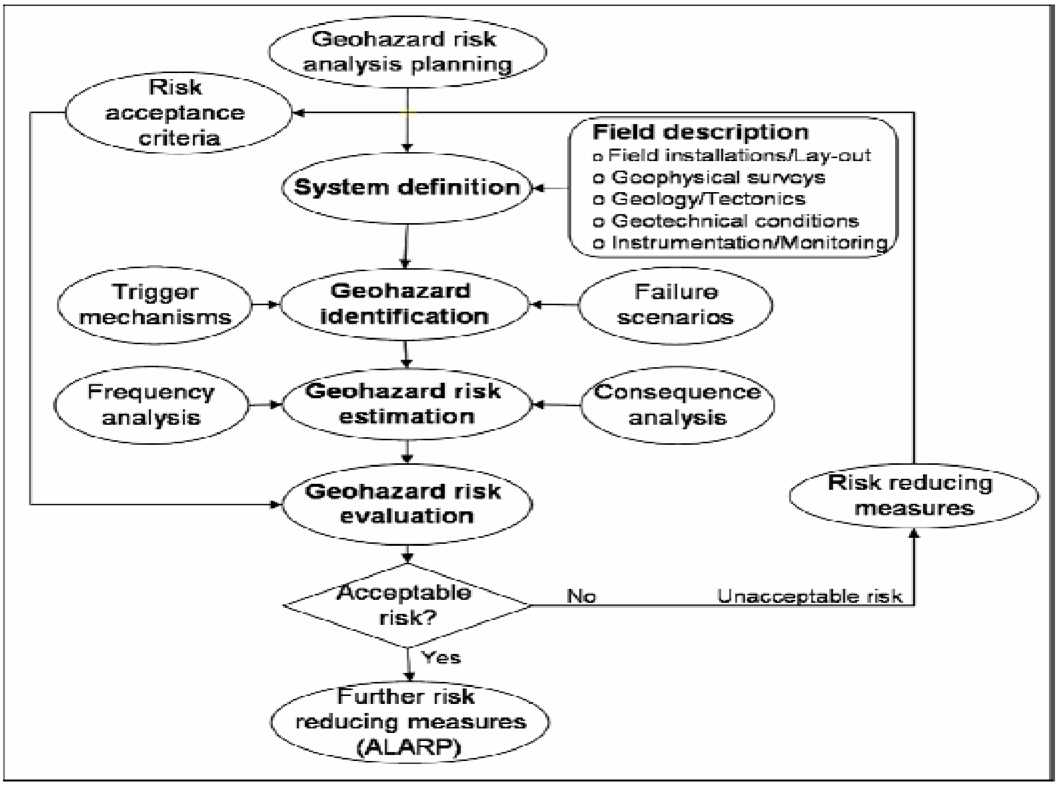


Figure 3.3 Geohazard risk analysis process [Nadim and Kvalstad, 2007]

3.3. Investigation of offshore geohazards

Lots of different phases are required in order to identify offshore geohazards. In early phases of design, scientists are based on local and regional information about geology, geography, tectonics and historic hazard information. All this information may be limited to some areas, as past investigations or any other projects may never happen before.

The investigations should include information about:

- Geological and geotechnical site conditions.

- Geological processes and human activities that can threaten the subsea structures.
- Human life, environment and facilities that could be exposed to geohazards events.

Reaching out into detailed analysis of the examined area can be succeed by seismic profiling, bathymetry and seabed features and specific information related on the project. Seismic profiling should indicate slides activity, buried marine transport deposits, mud volcanoes, deep-seated faults and faults to the surface. Also, a 3D seismic survey can show details of the local bathymetry that helps to detailed impression of the examined location. Moreover, specific information related to the project can provide geophysical data, seismic hazard assessment, assessment of soil parameters etc.

Phase 1. Pre-Drilling Activities	*Phase 2. Post-Discovery*	*Phase 3. Integrated Site Characterisation*
Screening of regional geological hazards	Preliminary engineering evaluation	Seismic inversion and development of final geotechnical criteria
Assess geohazards in prospect area	Plan high-resolution geophysical survey programme	Detailed geohazard assessment, analyses for special engineering issues
Assess hazards for specific well sites	Carry out high-resolution geophysical survey programme	Risk assessment
Team meetings and reporting	Prepare and process high-resolution geophysical data	Develop model with integrated site characteristics
	Complete preliminary site characterisation	Prepare integrated report
	Plan geotechnical site investigation	Team meetings and reporting
	Carry out geotechnical investigation	
	Sample preparation and shipping to laboratories	
	Geological lab testing	
	Geotechnical lab testing	
	Team meetings and reporting	

Figure 3.4 Summary of generalized investigation procedures [Randolph and Gourvenec, 2011]

All these surveys consist another specific discipline of geoscientist who tries to analyze data from multi-beam echo sounder systems, mounted on ships. Different methods to scan the instabilities and anomalies of the seabed are applied depending on water depths, inclination and accuracy needed for the future project. Some examples are shown on the pictures below.

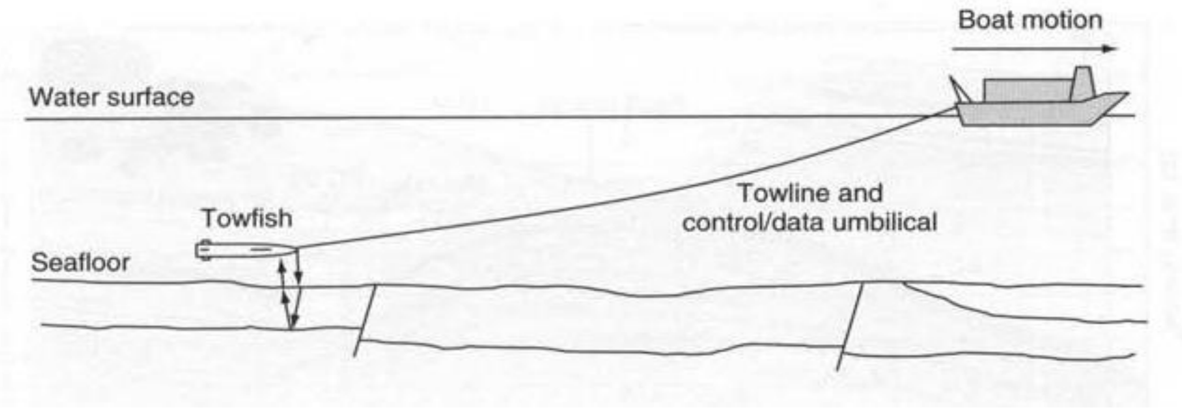


Figure 3.5 Town fish system [Dean, 2010]

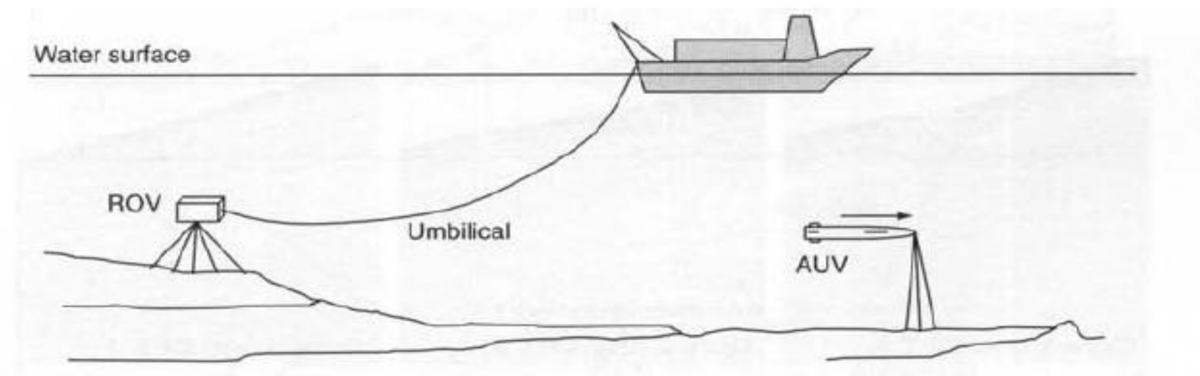


Figure 3.6 Remotely operated vehicles and autonomous underwater vehicles [Dean, 2010]

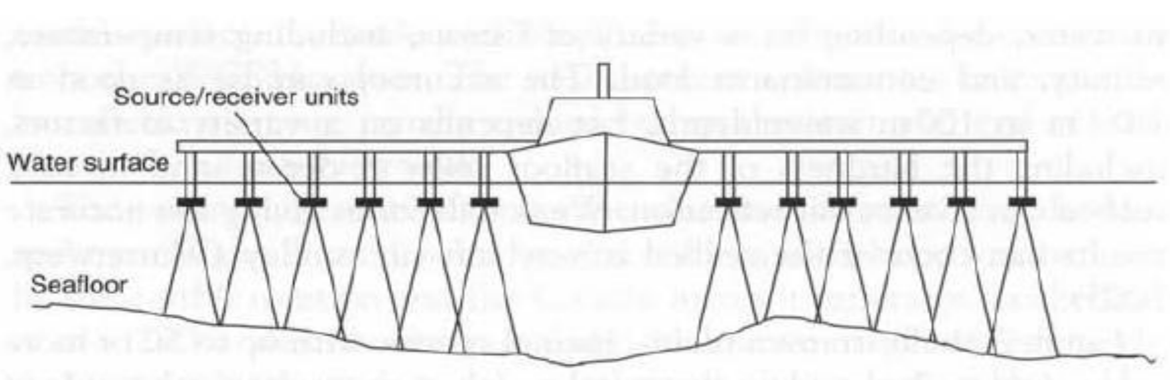


Figure 3.7 Multi-system array [Dean, 2010]

3.4. Emphasis on earthquake-related geohazards

We can characterize as marine geohazards all the slope failures, tectonic and non-tectonic faulting, strong ground movements, liquefaction, salt diapirs, mud volcanoes, shallow gas, gas hydrates and scour by currents. Also, in some cases we can describe as offshore geohazards the hydrodynamic forces caused by wave and tsunami actions. Last, slopes into the seabed may be described as an offshore geohazards given that they have potential to be unstable and fail, resulting landslide events.

Great interest for us seems to have the offshore geohazards related to seismic events, because they can provoke large displacements to subsea structures. The main categories of those geohazards are the following:

3.4.1. Soil liquefaction phenomena

Repeated cyclic motions of saturated cohesionless soils can cause liquefaction. During this event, we observe loss of strength, due to build-up of pore water pressures during dynamic loading that causes solid soil to behave temporarily as a liquid. This phenomenon occurs in unconsolidated soils affected by seismic S-waves. Hence, both gravity based and pile founded structures which are based on this category of soils, have lots of possibilities to have their strength decreased and be liquefied.

According Robertson et al. (1996), the classification system of soil liquefaction related on earthquakes consists of two main categories:

1. *Flow liquefaction*, used for an undrained flow of a saturated soil, when the static shear stress exceeds the residual strength of the soil. Triggering mechanisms can be either cyclic or monotonic shear loading.
2. *Cyclic softening* used to describe when large deformations occurring during cycling shear would tend in undrained monotonic shear.

The results of such an event may differ, depending on loads, frequency and the exact location of the seismic event. There are eight main consequences can be provoked in soil liquefaction related on earthquakes:

- Sand boils
- Flow failures of slopes
- Lateral spreads
- Loss of bearing capacity
- Ground settlement
- Failure of retaining walls
- Buoyant rise of buried structures
- Ground oscillation

3.4.2. Active faults

Fault movements can be occurred during seismic events. Faults are planar discontinuities between blocks of rock that have been displaced in a parallel direction. Active faults can be classifies depending on their recent activities. Hence, different methods of classification can divide the active faults regarding the frequency of their movements, or the exact moments of their recent events.

There are three main types of faults depending on the direction of movements:

- Normal fault
- Reverse fault
- Strike-slip fault
- Thrust fault

The different types of active faults can be easily understandable, if we have a look at the following figure.

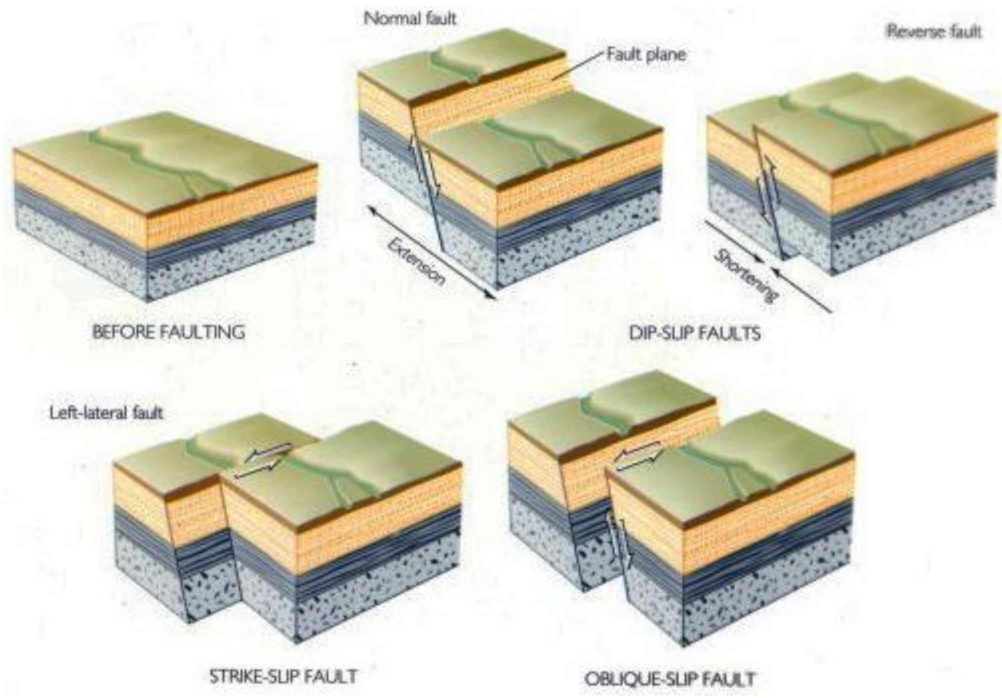


Figure 3.8 Different types of active faults [http://www.gaia-legacy.ch/the-geomantic-lines]

The most complicated issue related on active faults during a seismic event, is how they can damage the subsea structures. The parameters involved in the process and affect the results of such an event are:

- Location of the active fault
- Direction of movements
- Orientation of fault plane
- Depth of the fault
- Amount of fault displacements

Estimating the results related on soil liquefaction phenomena or an active fault is an extremely depending topic, which needs further focus on academic background and technical issues. For the current thesis, we will not be able to focus on all the parameters involved, but we try to refer them briefly in order to help any readers to have a general idea of earthquake-related geohazards.

3.5. Submarine Landslides

At this point, we would like to emphasize on submarine landslides, as it is the examined geohazard of the current study. We selected to analyse and focus on this specific geohazard can provoke large displacements and may interrupt the operation of an offshore pipeline. The recent and future projects in Middle East and Mediterranean Sea will face that challenge given that the geological and geophysical profiles and the seismicity of the area.

3.5.1. Definition and Characteristics of submarine landslides

Landslides are mass ground movements. Landslides can be occurred in onshore or offshore environment. *Onshore landslides* can be caused by seismic events, which increase lateral driving forces, or by wet weather, which reduces the resistance into slope movements.

Offshore landslide events can be occurred in a subsea pipeline, so we will focus on this category. Offshore landslides can be triggered by seismic loads or by storm waves. In some cases, triggering mechanisms of landslides movements can be mud volcanoes or seafloor erosion.

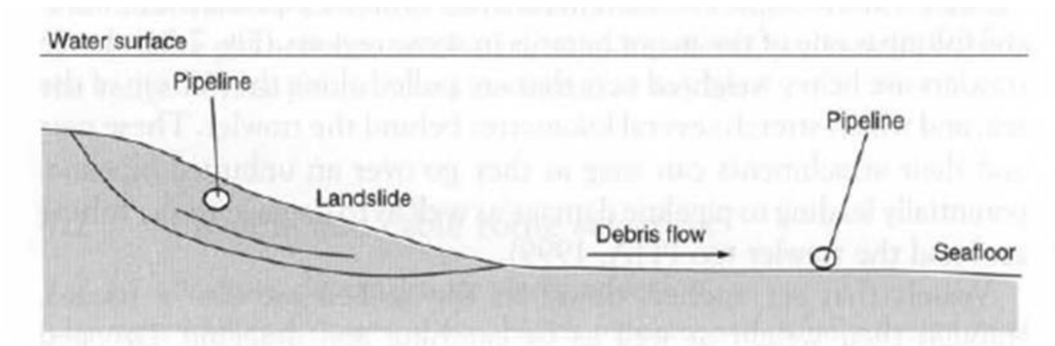


Figure 3.9 Landslide movement [O'Rourke, 2012]

3.5.2. Characteristics of offshore landslides

Seismic waves provoke dynamic or cyclic loading, which can lead to excess of water pressure of soils. As a result, shear strength is reduced of soils and then mass movements can be occurred. The triggering process is the same as in onshore landslides for earthquake events. However, for wave caused landslides events the process is highly different. The reason is the pressure on ocean seabed is larger under the storm wave crest and lower under the wave trough. Actually, the earthquake related landslides are more frequent than the wave caused landslides events.

The ground movement is downslope and according scientist surveys, the slope angle is much smaller than onshore landslides. The most common values for landslides angles are between 3°-5° , but some landslide events have been occurred with lower angles of 0.5° which maybe caused due to soil liquefaction phenomena. This can be confirmed by Figure 3.9, which shows the range of slope angle from 339 landslide events examined.

Finally, we should examine the landslides movements in both axial and vertical directions because the response of offshore pipeline is different in these two cases. Also, we should clarify that the forces of landslide events in offshore environment are lower than those provoked in a buried pipeline.

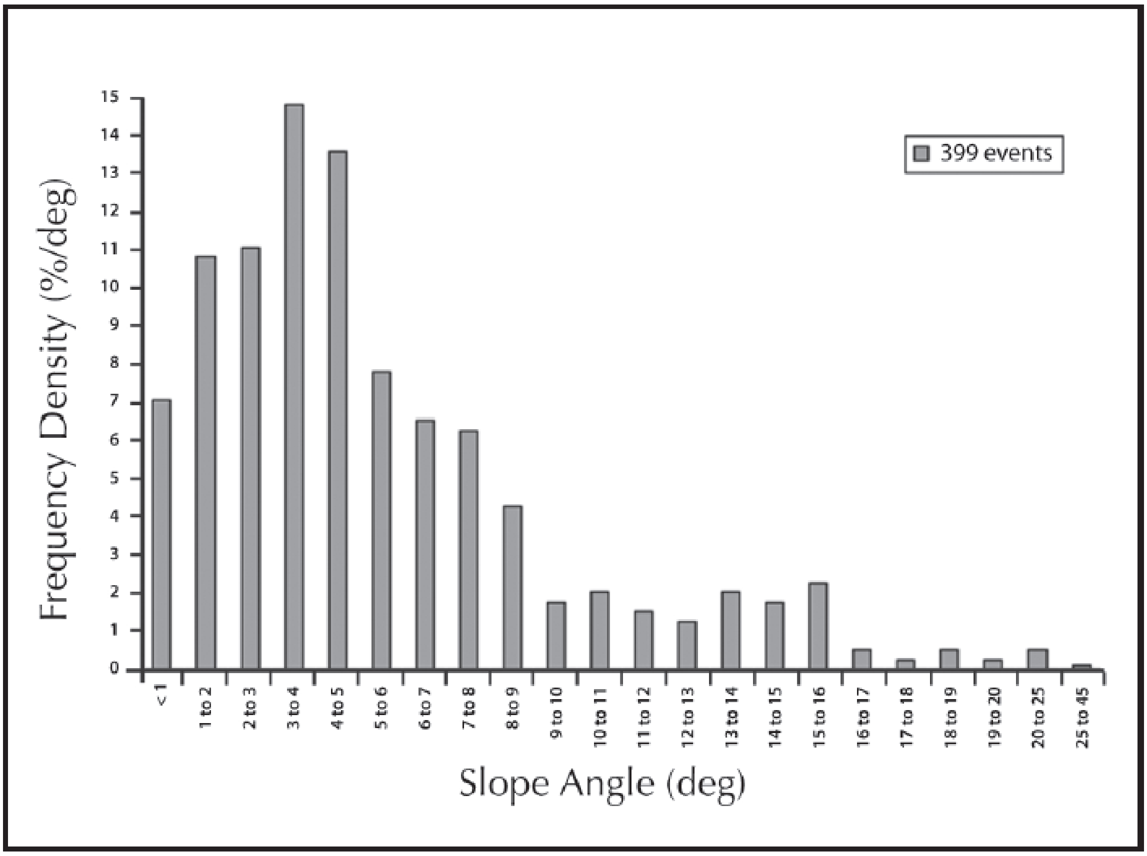


Figure 3.10 Frequency distribution for the average slope angle of submarine landslides [O'Rourke, 2012]

3.5.3. Potential damages of offshore pipelines

A simplified model of an offshore landslide is shown below in Figure 3.10. The characteristics run-out distance, R, and length, L, may divide the importance and the results of landslide event. Moreover, the response of offshore pipelines depends on the orientation of pipeline to the direction of ground movement. It also depends on the maximum available force of soil-pipe interface.

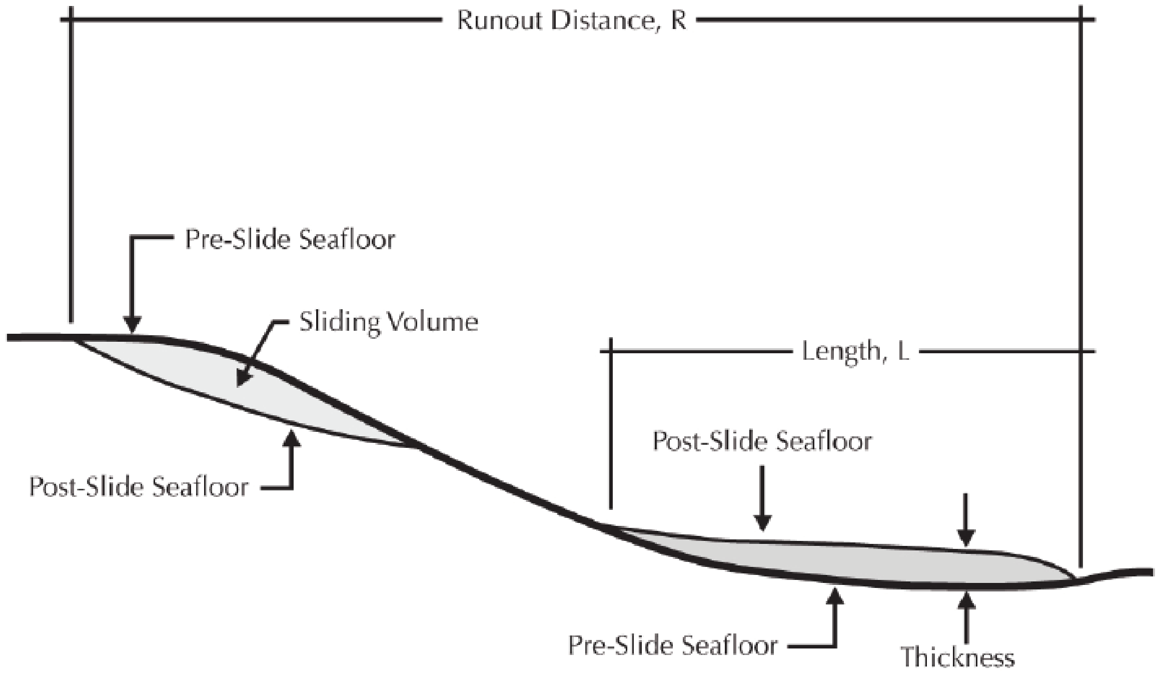


Figure 3.11 Geometry of an offshore landslide [Randolph & Gourvenec, 2011]

The landslide events are characterized as the most hazardous of geological phenomena for two reasons:

- The great variety of landslide events and their characteristics
- The lack of accurate simulation models to predict the behavior of landslide movements

Geoscientists try to avoid those areas, if possible, while designing the route selection of the pipeline. The maintenance works in offshore environment is another issue which struggle the process.

Some of the possible consequences to the offshore pipelines are the following:

- Lateral displacements of the pipeline

- Vertical displacements of the pipeline
- Excess of plastic behavior of soil characteristics, which support the pipeline
- Free-spanning area, which means that the soil properties that support the pipe, have removed
- Buried area of pipeline under the sedimentation of soil properties

4. Analytical solutions

Pipelines are often subjected to resist to loading caused by landslides either in offshore or onshore environment. The main principles are the same, as the active loading will damage a specific length of the pipeline depending on the width of the landslide. Then, deformations will come up in this specific area and they will be stable and permanent. This problem is extended in the current chapter using two different analytical methods suggested in the literature, in order to give an easy formula to calculate the deflections in case of slide events.

Searching for an analytical solution to validate the results of numerical modelling seems to be so challenging in this specific topic: offshore landslides on offshore pipelines. Given that offshore engineering does not allow easy access for maintenance works, it is a great need to predict in advance the behavior of offshore pipelines on landslide events. Despite the extended activities of oil and gas facilities in specific areas, it was hard to find accurate methods on literature seismic events on those areas are not frequently taken place. Finally, we found some research articles which tend to define the failure, which are used as an initial and approaching method of the behavior of pipelines into accidental events.

4.1. Analytical solution of Randolph et al.(2010)

The analytical solution of Randolph et al., 2010 is actually the motivation of our numerical study, as we tried to validate it using the finite element software, ANSYS.

In this section, we will expand the current method as suggested from academic researchers referring the limitations and the equations derived from this study.

4.1.1. Description of the problem

In the current master thesis, we selected an analytical solution as suggested from Randolph et al (2010). This solution gives us the chance to approach the failure of the offshore pipelines with a linear equation. The academic research focused on the possibility of mudslides triggering caused by hurricanes Ivan and Katrina in the Gulf of Mexico and on the possibility caused by debris flows.

Previous research studies examined different triggering mechanisms, but in general the problem‘s main idea is the same: the active loading will damage a defined length of the pipeline regarding the width of the landslide. Then, the pipeline will be restrained by frictional resistance which acts horizontally to the pipe and by normal passive resistance, as designed in figure below.

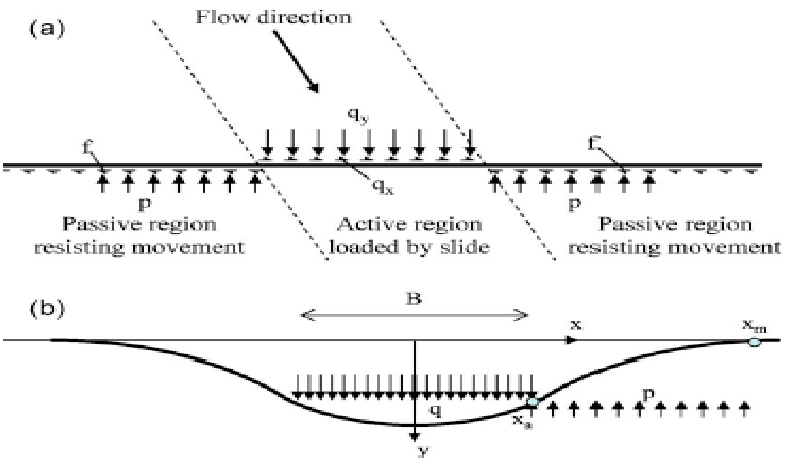


Figure 4.1 Idealization of loading and deformation of the pipeline [Randolph et al, 2010]

In Figure 4.1 the following symbols are being used:

- q : landslide loading which corresponds to q_x and q_y directions
- p : passive normal resistance
- f: axial sliding resistance

All these quantities are defined as in terms of the load per unit length. The other characteristics of pipeline are the external diameter, D, wall thickness, t, and Young's modulus, E. The results are presented in terms of nondimensional values.

At this point, we would like to clarify that for large movements of landslides, the focus is considered to be in state steady conditions. Also, there were various models analyzed before the magnitudes of the active loading and resistance of the pipeline, which expressed generally in terms of friction factor and passive resistance. However, the present study is focused on a parametric equation of pipeline response as a function of input parameters (pipeline properties and pipe-soil characteristics).

4.1.2. Limitations of the parametric study

This study is based on certain idealizations and assumptions which make the solution of the problem more easily approachable. So, it does not describe the complex problem with all the quantities involved in an offshore pipeline, but we use some limitations to simplify the problem and have results of an initial study.

Hence, the limitations are the following:

1. The seabed of the pipeline is flat, so that the pipeline deflection is not restricted. In reality, the critical sections of submarine pipelines are often associated with canyons or gullies. These may restrict the lateral movement of the pipeline but will also tend to divert a debris flow to follow the canyon. Such complexities are out of the scope of the paper.
2. The initial tension T_o(operational effective tension) is equivalent to zero.
3. The pipeline can be extended without limit in both sides of the slide.
4. The length of the pipeline is finite. This approach does not take into consideration the case of pipeline anchoring system, which means that the length of pipeline is of finite length.
5. Inclination loading is equivalent to zero. The lateral and axial loading of landslides cannot change a lot the results, as the slides which strike the pipeline at an angle have values between 1-6^o, which means that they will have similar values when analyzed in two q_x and q_y directions.

4.1.3. Solution

The initial study focuses on the case where the slide loading is perpendicular to the pipe. So, using the approximate analytical solution this problem can be validated with a numerical study with pipe-soil interaction simulated by elastic-plastic springs along the length of the pipe.

The problem as it is shown in Figure 4.1 can by analyzed within active and passive zones as follows:

$$EIy''' - Ty'' = q \tag{4.1}$$

In terms of nondimensional form, we could rewrite this equation:

$$\frac{EI}{EAB^2}Y''' - \frac{T}{EA}Y'' = \frac{qB}{EA}$$

(4.2)

Where Y=y/B and X=x/B in order to have nondimensional results. The solutions of this equation are the following:

$$Y = -\frac{q}{2BT}X^2 + c_1 + c_2X + c_3 sinh\gamma X + c_4 cosh\gamma X \tag{4.3}$$

which is applicable for the $0<X<X_a$

and

$$Y = -\frac{q}{2BT}X^2 + c_5 + c_6X + c_7 sinh\gamma X + c_8 cosh\gamma X$$

(4.4)

which is applicable for $X_a<X<X_m$

After applying boundary conditions

Y’=Y’’’=0 at X=0

Y=Y’=0 at $X=X_m$

We have a parametric equation which gives us the opportunity to define the response of the pipeline. The quantities involved are explained in Table 1 below. The cases differ depending on the ratio of B/D , so we distinguish the results into two different groups:

For the most slide widths B/D>200, the equation is :

$$\frac{y_{max}}{B} = \frac{1qB\,(1+\frac{q}{p})}{8EA\,(\frac{\sigma_t}{E})}$$

(4.5)

where $$\frac{\sigma_t}{E} = 0.28(\frac{B}{D})^{0.075}(\frac{qB}{EA})^{0.75}(\frac{p}{q})^{k_2}(\frac{f}{p})^{0.22}$$

(4.6)

and $$k_2 = 0.075 - 2.0(\frac{B}{D})^{-1}(\frac{qB}{EA})^{-0.2}$$

(4.7)

Otherwise, for the most narrow slides, when B/D<200, the equations differ as follow:

$$\frac{y_{max}}{B} = 0.23(\frac{B}{D})^{0.76}(\frac{qB}{EA})^{0.54}(\frac{p}{q})^{k_3}(\frac{f}{p})^{-0.15}$$

(4.8)

and $$k_3 = -0.6 - 0.5\left(\frac{B}{D}\right)^{-1}\left(\frac{qB}{EA}\right)^{-0.37}$$

(4.9)

Then, we calculated the values of those equations depending on the slide width and we validated the results with numerical modelling, in ANSYS software using Finite element method. The results will be presented in the next chapter to indicate the accuracy of the method.

Table 4.1 Quantities used to calculate response of pipeline

Input parameters	Symbols
Active loading of pipeline	q
Passive normal resistance	p
Axial frictional resistance	f
Outside Diameter	D
Length of landslide loading	B
Pipeline axial stiffness	EA
Pipeline bending rigidity	EI

4.2. Analytical solution by Yuan et al. (2014)

At this point, we would like to present another academic study which tries to enlighten the complexities of the problem when landslide loading effects an offshore pipeline. This current study approaches the solution in a similar way, as it is considered that the pipe has a linear behavior in comparison with the plastic behavior of the soil characteristics which support the pipe.

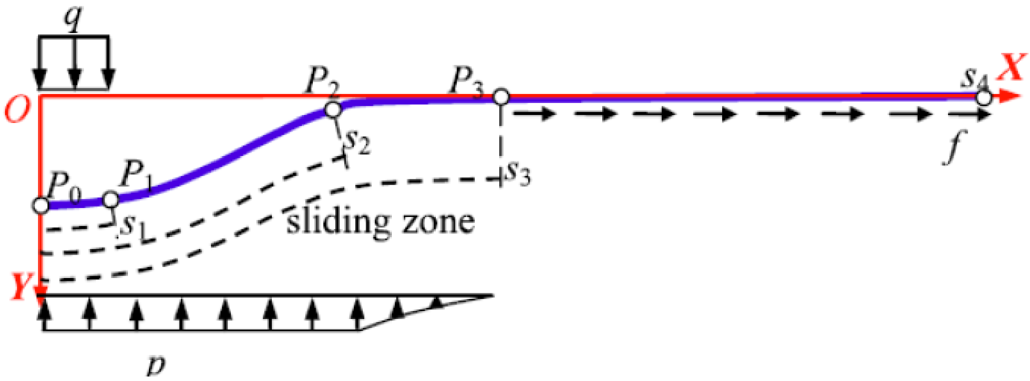


Figure 4.2 Suggested model of pipeline loading and deflection [Yuan et al., 2014)

As we can easily imagine, the problem has a similar solution. However, this specific study does not provide any parametric equation but the results are validated by differential equations. Definitely, it is not so easy approach as the previous one so we will not extend our analyses based on this analytical approach. However, we can compare some results with the diagram provided by this study and come from various numerical and analytical analyses of this work.

The solution is based on beam theory of Euler-Bernoulli and is applied in different parts of the pipe depending on the loading. The quantities involved in this study are similar with the solution suggested by Randolph et al., 2010. In order to describe the pipeline properties, the values of outside diameter, *Do*, and inside diameter, *Di*, the resistance of passive zone, p, the slide loading, q, and Young's Modulus, E, are necessary.

So, we will present the results of those two analytical approaches and the numerical analysis for specific values of quantities used. The chart belonged to this current study is shown below in Figure 4.3. The values are specified in the next chapter where the analyses are described in detail.

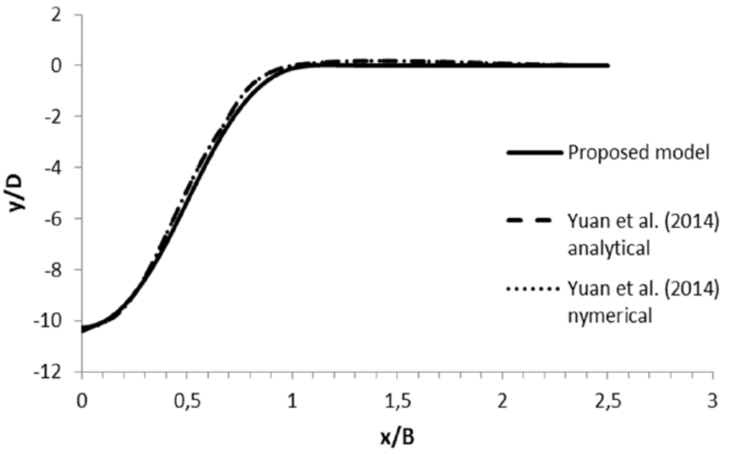


Figure 4.3 Typical results showing the deflection of pipeline [Yuan et al., 2014|

5. Numerical Modelling

This chapter explains in detail all the steps and methods used in ANSYS in order to validate the analytical solution. At first, we should describe analytically step by step how we created the geometric model in software ANSYS using the method of finite elements. Then, we will explain the soil characteristics and we will show the results of both the numerical and analytical methods.

5.1. Initial testing of the numerical method

Trying to validate an analytical solution is a complex procedure where we need lot of time to correct and search the steps needed before creating the right model. In order to secure that our methodology is correct, we need to clarify that we start properly the numerical model.

The difficult part of modeling was that the problem we analyzed is an advanced case. As described before, we are talking about a linear and non-linear behavior at the same time for the contact pair of the pipe and soil interaction. Apart the fact of the contact elements, the paper was missing important values of nonlinearity of the soil characteristics, which makes us, proceed to literature or other individual projects before to define the most common cases of pipe-soil interaction. Also, the paper itself describes the numerical method in similar software of Finite Element Method (ABAQUS) which did not help us to gain time and guidance.

Unfortunately, previous projects have not analyzed before a similar model in ANSYS, so lot of valuable time spent while searching the options of the software in order to accomplish the final model. Taking into account those parameters, we would like to eliminate the errors and be sure for the final results as much as we could. So, using ANSYS with no additional guidance and help needed some validation from the beginning.

5.2. How to test the numerical method: case of beam bucking under distributed loading, fixed in two ends

In that point, we would like to remind the problem and trying to divide it in stages, where we could eliminate the risks and be sure for the results. As we can see in the Figure 4.3, as referred in the previous chapter, the middle area of the pipe is the first one where we will try to create in ANSYS. The areas on the right and left side are the passive zones, where we have to insert the soil characteristics. In the first stage, we will ignore the influence of those areas and try to create the pipe under distributed loading.

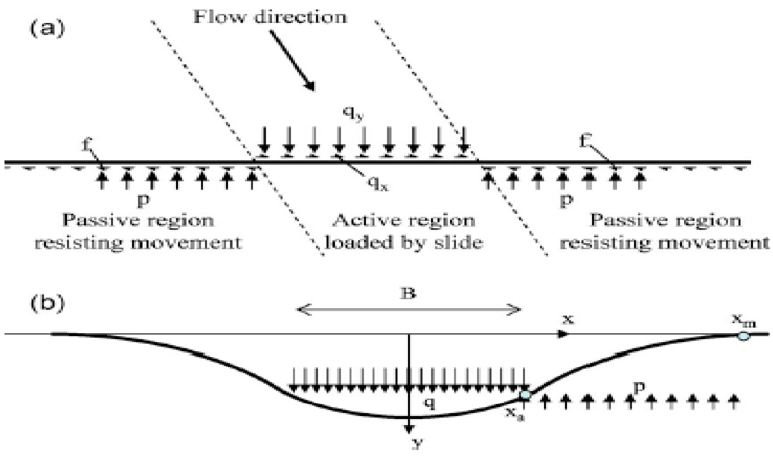


Figure 4.1 Idealization of the pipe deflection[Randolph et al, 2010]

So, starting to create the geometry of the pipe itself, means using specific values of the quantities involved, Young's Modulus, Poisson ratio, outside diameter and wall thickness. Also, the landslide loading which is specified from forces used in the current study and the boundary conditions in two ends, accomplish the first test in the software.

The pipe has the same behavior of a beam under distributed loading. This helps us because it is easy to find the analytical solutions from structural design analysis and validate the results with the numerical method.

5.3. Summarized guide to ANSYS software-Design of the pipe

In ANSYS, we have different options to create the models. In the current study, some of the steps needed to create the model are shown analytically in order to offer help to those who have not used before the software. It could be more helpful, if there was such a collective work before starting this analysis so here is an effort to give some advice for future projects.

The software of ANSYS is divided into three main categories: *Preprocessor, Solution and General Postprocessor.* In the first one, we have to design the model, in the second one we apply the forces and define the boundary conditions, Finally, in the area of Postprocessor belong the results of the analysis.

5.3.1. Selection of the right beam element and why

As we can see from the Figures below, there are lots of different options for creating a pipe in 3-D modelling. We could use the option of Beam-> 2-node 188 or 3-node 189 and select Help, in order to read the description of the element. Also, for a 3-D pipe we could use the Solid->Brick 8 node 185.

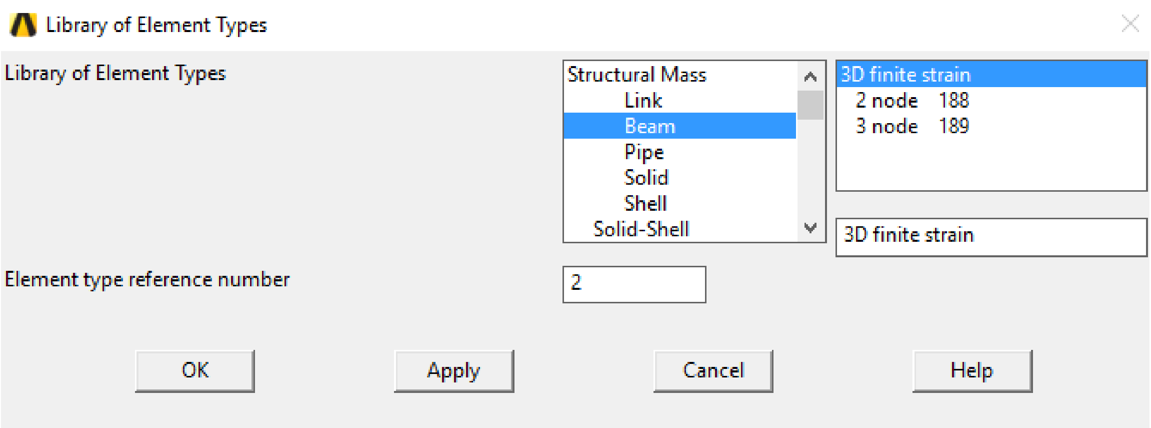


Figure 5.1 Type elements in ANSYS

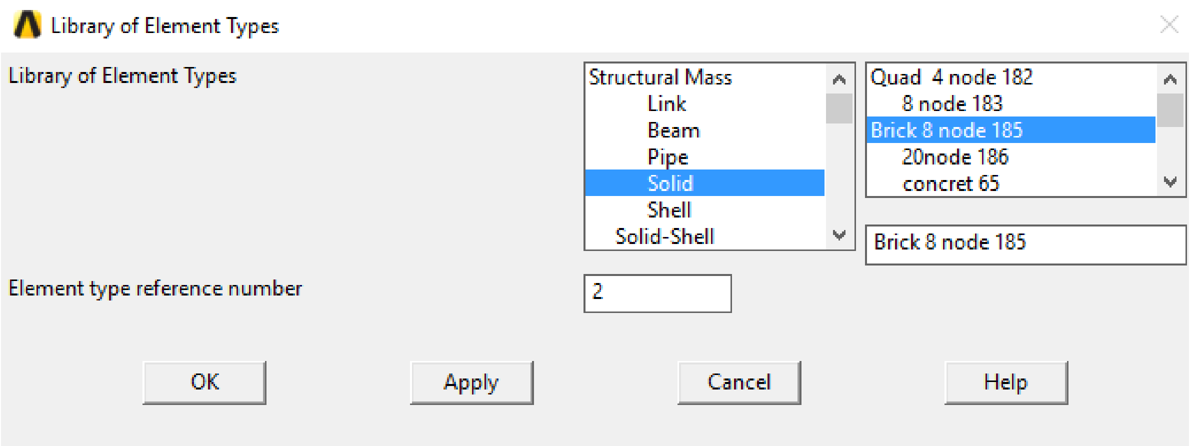


Figure 5.2 Type elements in ANSYS

The element we selected has the limitation to be based on Timoshenko theory, which means that this is applicable to large pipes. Theoretically, the rule is that the ratio $\frac{Length}{Cross\text{–}section\ area} > 300$. This option effects how the software can calculate the large or the small displacements in the element provided, and this is important to select the appropriate one to let the ANSYS provide us accuracy to the results.

For this current study, the right element was **PIPE 288.** The PIPE288 element is suitable for analyzing slender to moderately stubby/thick pipe structures and it is based on beam theory. Shear-deformation effects are included. PIPE288 is a linear, quadratic, or cubic two-node pipe element in 3-D. The element has six degrees of freedom at each node (the translations in the x, y, and z directions and rotations about the x, y, and z directions). The element is well-suited for linear, large rotation, and/or large strain nonlinear applications.

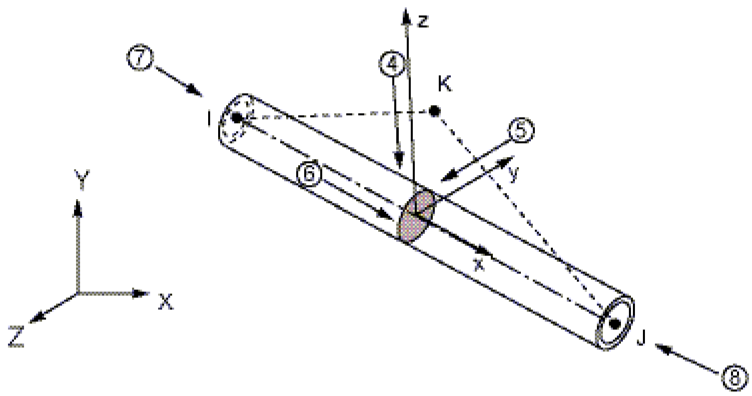


Figure 5.3 Geometry of PIPE 288

5.3.2. Design of the pipe

The characteristics we used are the main quantities to describe the pipe, so we could have the first part already done and then to proceed in the contact pair area. The values used are shown in Table 2, which are the same of case B2 as referred in the model of Randolph et al. (2010).

Table 5.1Inpout parameters of the first analysis

Inpout parameters	**Values (SI)**
Length of the pipe, B	100 m
Landslide loading, q	21600 N/m
Outside diameter, D	0.72m
Wall thickness, t	D/4=0.029
Young's Modulus, E	$210*10^9$
Poisson ratio, v	0.3

The whole process of designing is provided on internet sources or even in the help box of ANSYS, but in general the methodology consists of :

- Selecting the element type(PIPE 288)
- Define material properties(STRUCTURAL,LINEAR, YOUNG'S MODULUS, POISSON RATIO)
- Write the values of the section(PIPE, DIAMETER, WALL THICKNESS)
- Insert the points in the two ends and create the line in the middle of the pipe. (POINT 1,POINT 2) ->(0,0,0),(0,100,0)
- Mesh the line selecting the number of elements or the length of each element.(Meshing per 1 meter length)
- Apply boundary conditions in two ends(ALL DOF=0)
- Define loads in the length of the pipe(PRESSURE in J DIRECTION to insert disributed loading)
- Select the option ESHAPE in order to have the 3-D modelling

Figure 5.4 shows how the model is after applying all the previous steps.

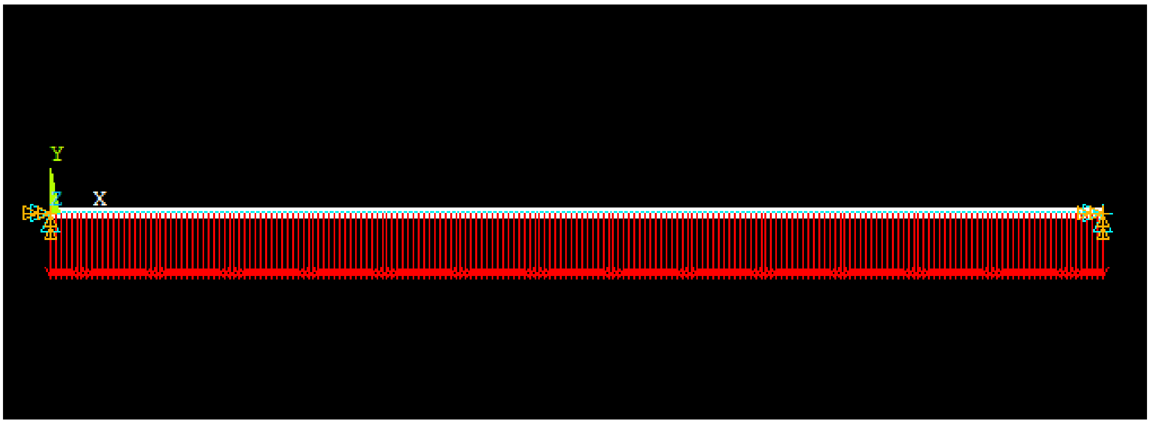


Figure 5.4 Modelling of the pipe

5.3.3. Results of numerical modelling

After all these steps, we should have the results with ANSYS in the General Postprocessor area. Figures 5.5 and 5.6 show how ANSYS gives the results of deflection and bending moment.

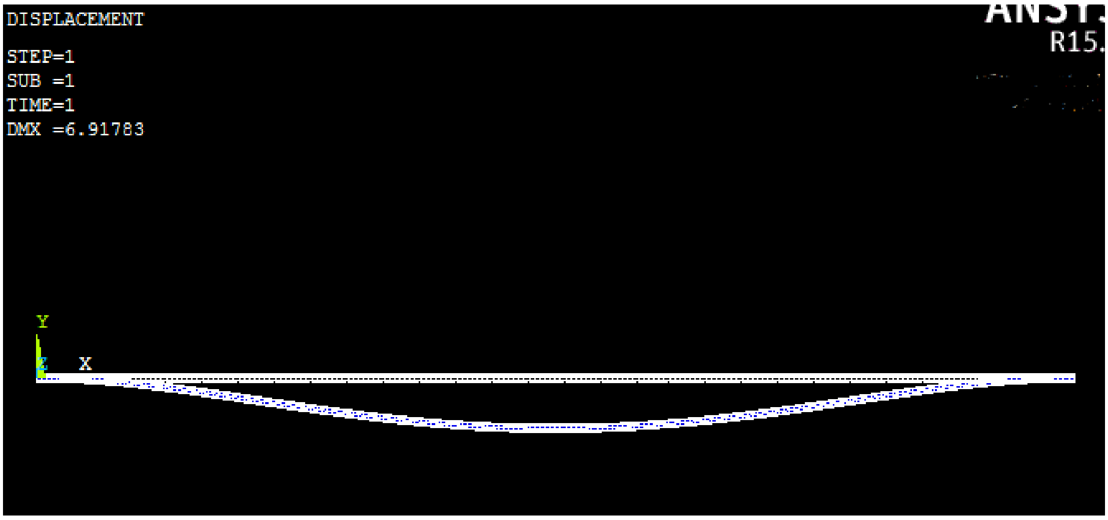


Figure 5.5 Plot results of deflection of the pipe

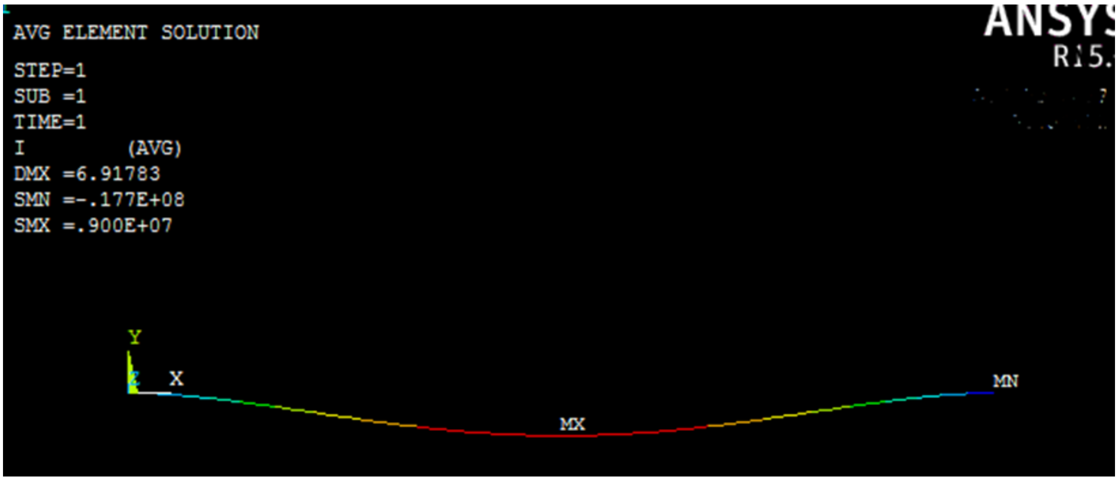
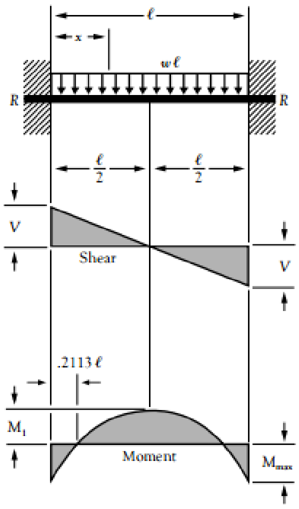


Figure 5.6 Plot results of bending moment of the pipe

5.4. Analytical solution and validation of results

As it is shown in the Figure 5.6, the maximum deflection and bending moment can be calculated by the equations on the right side.



$$R = V \dots = \frac{w\ell}{2}$$

$$V_x \dots = w\left(\frac{\ell}{2} - x\right)$$

$$M_{max} \text{ (at ends)} \dots = \frac{w\ell^2}{12}$$

$$M_1 \text{ (at center)} \dots = \frac{w\ell^2}{24}$$

$$M_x \dots = \frac{w}{12}(6\ell x - \ell^2 - 6x^2)$$

$$\Delta_{max} \text{ (at center)} \dots = \frac{w\ell^4}{384EI}$$

$$\Delta_x \dots = \frac{wx^2}{24EI}(\ell - x)^2$$

Figure 5.7 Equations of beam fixed in two ends under distributed loading (http://www.awc.org)

As described in Table 2, the parameters are the following:

Table 5.2 Inpout parameters of the first analysis

Inpout parameters	**Values (SI)**
Length of the pipe, B	100 m
Landslide loading, q	21600 N/m
Outside diameter, D	0.72m
Wall thickness, t	D/4=0.029
Young's Modulus, E	$210*10^9$
Poisson ratio, v	0.3

So, in order to calculate the maximum deflection:

- W=q= 21600 N/m
- L=B=100 m
- $R_o=D_o/2=0.36$ m
- $R_i=R_o-t=0.321$ m

$I=\pi(R_o^4-R_i^4)/4= \pi(0.36^4-0.321^4)= 0.0038775\ m^4$

$$Ymax= \frac{WL^2}{384\ EI}=\frac{21600*100^2}{384*210*10^9*0.0038775}=6.91\ m$$

$Mmax= -WL^2/24= 9{,}000{,}000\ Nm$

As we can see the results are the same both in analytical and numerical method, so till now our modelling is designed properly. So, we can move on the next stage to insert the soil pipe interaction to the model and start the parametric study.

5.5. Insert soil-pipe interaction in ANSYS

Now, we have to insert the pipe characteristics. For the soil-pipe interaction we need to insert a target surface, which will support the pipe. For this purpose, we selected **TARGE 170** element. Figure 5.8 shows the simplified model of soil-pipe interaction as suggested by Randolph et al.

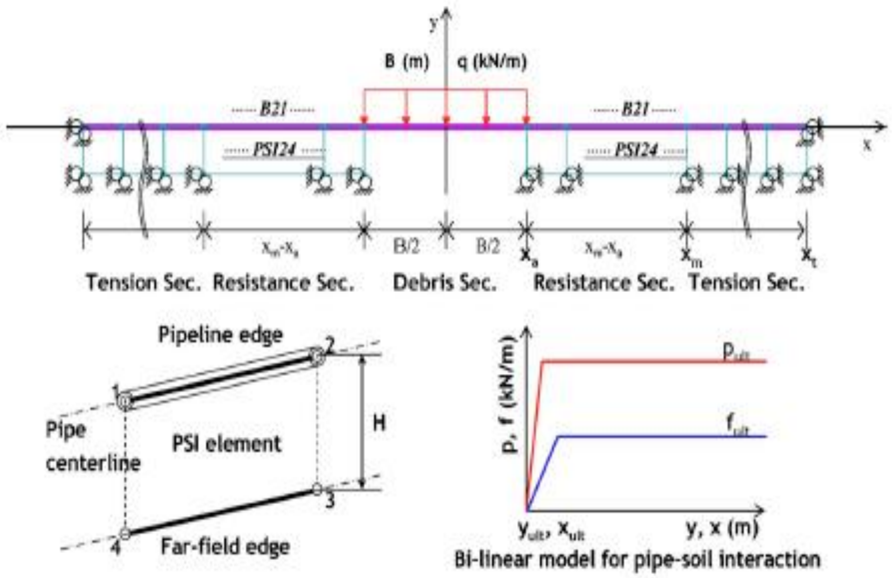


Figure 5.8 Simplified model with soil characteristics [Randolph et al.,2010]

5.5.1. Selection of TARGE 170 for soil-pipe interaction

TARGE170 is used to represent various 3-D "target" surfaces for the associated contact elements. The contact elements themselves overlay the solid, shell, or line elements describing the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE170. This target surface is discretized by a set of target segment elements (TARGE170) and is paired with its associated contact surface via a shared real constant set.

We can impose any translational or rotational displacement, temperature, voltage, and magnetic potential on the target segment element. You can also impose forces and moments on target elements. In the figure 5.9, we can see how the surface can be defined depending on the known nodes of the model.

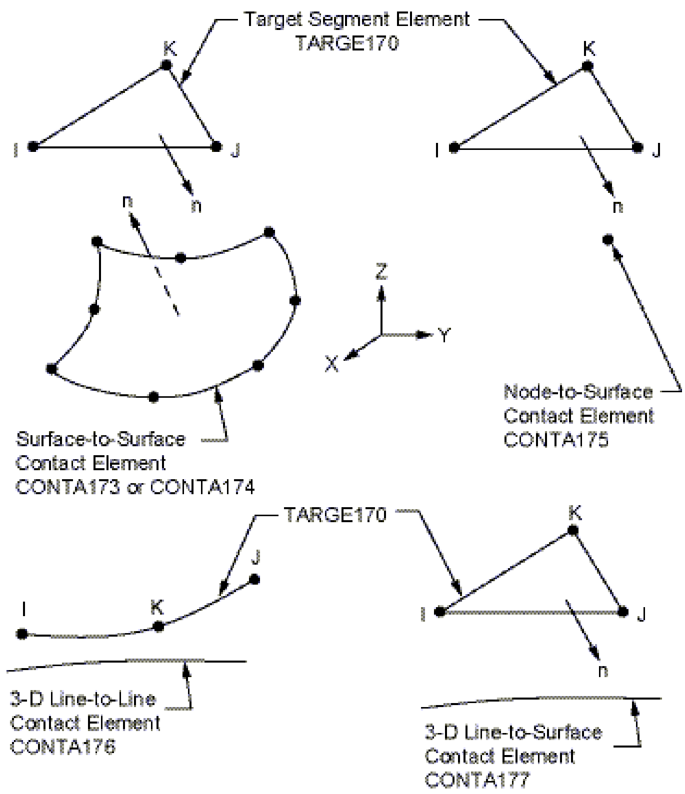


Figure 5.9 Contact surface TARGE 170 and contact pairs as described in ANSYS

Contact pairs in ANSYS can be characterized by various combinations: surface-to-surface contact element, node-to-surface contact element, line-to-line or line-to-surface contact element. Our suitable contact pair is surface-to-node contact pair given that we used two nodes before in order to create the pipe.

5.5.2. Design of soil pipe interaction

We used the previous model, which was 100 m pipe length and we added two more points on the right and left side. Point (200, 0, 0) and Point 4(300, 0, 0) can give us the

image of how is the pipe in Case B2 of Randolph et al. (2010).

Following the steps below, we can create a surface:

- Create an extra node in the cross-sectional area of the pipe, which will help us to define a target surface in 3-D modelling. For example, the outside diameter is 0.72 m and the middle zone is defined in (0, 0) XYZ coordinate system. The range in z-direction is between (-0.36, 0.36) so we created the point 5(0,0,-0.36) and point 6(0,0,36). The same methodology was used between the length 200-300 m of the pipe in order to create the supporting areas in both sides.
- Define the surface between those nodes in order to cover the area, where the pipe is supported.
- Create the contact pair, use as target surface the areas which support the pipe and then as contact area the nodes of the pipe.
- Automatically, the contact pair is created and shown in ANSYS as in the figure below.

The process now is completely the same as before. Applying the meshing, forces and boundary conditions is needed in order to have the results from the software.

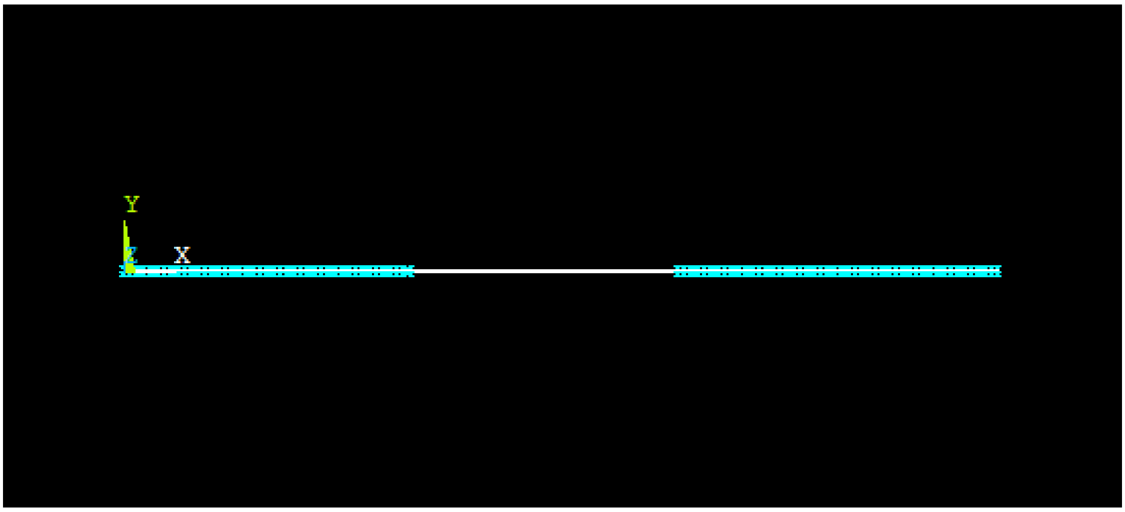


Figure 5.10 Pipe with soil characteristics

At this point, we have to clarify the other input parameters we used in the passive zones. Table 5.3 shows the values of passive normal resistance and axial frictional resistance. Also, the values of the plastic area of soil characteristics are provided.

Table 5.3Values of soil pipe interaction

Additional Input parameters	**Values(SI)**
Passive normal resistance, p	10,800 N/m
Axial frictional resistance, f	5,400 N/m
Fy,Fu,	490,000 , 531,000
ε	3%

5.6. The results and validation

After applying al the stages, we have finally the correct model. We applied the forces as described before in the appropriate areas and the boundary conditions in two ends are equal to zero. In the figures 5.11 and 5.12, we can see the maximum deflection and stress of the case and we can compare it with the analytical results. Also, in the last figure, the result can be confirmed using the chart derived from the analytical study of Randolph et al., 2010.

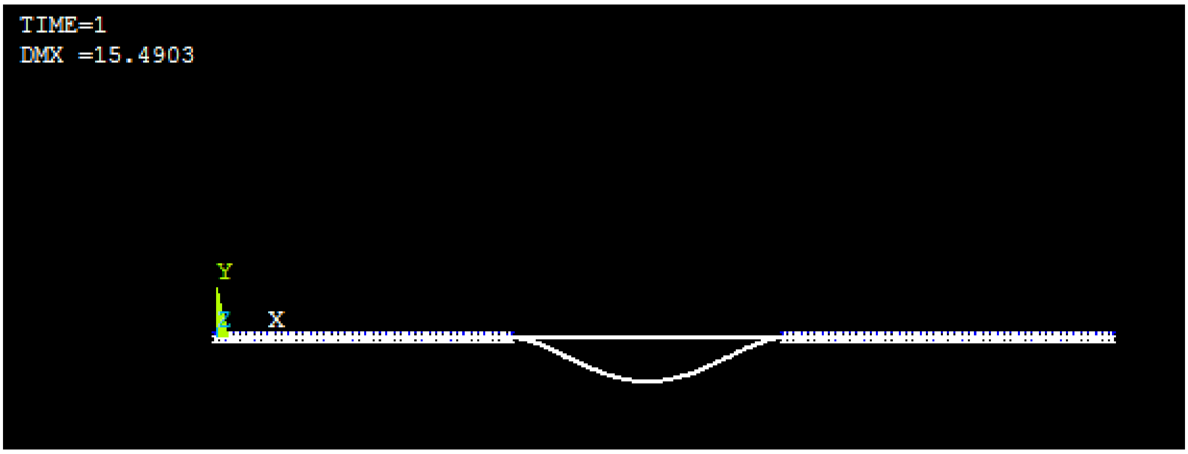


Figure 5.11 Maximum deflection of the pipe

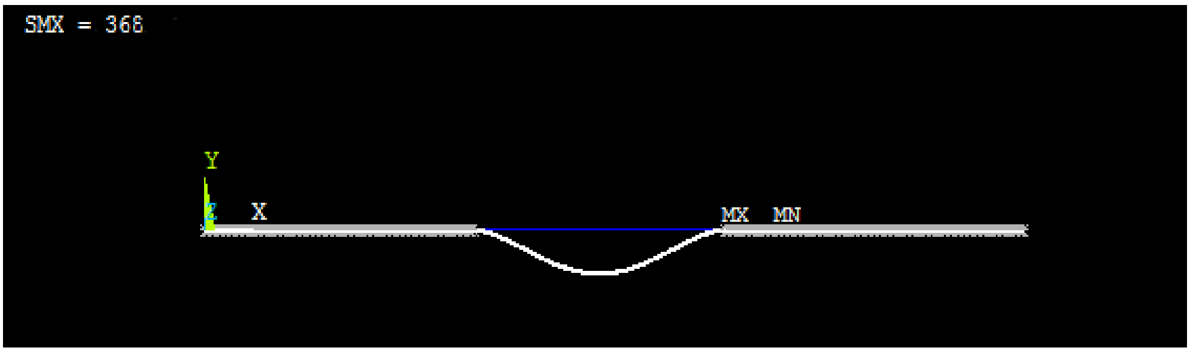


Figure 5.12 Maximum stress of the pipe

From numerical analysis, the deflection is 15.490 m and the maximum stress is 368 MPa. Using the equations, the results are similar. Therefore, we can proceed to a parametric study and extend the analyses.

$$\frac{\sigma_t}{E} = 0.28\left(\frac{B}{D}\right)^{0.075}\left(\frac{qB}{EA}\right)^{0.75}\left(\frac{p}{q}\right)^{k_2}\left(\frac{f}{p}\right)^{0.22}$$

(5.7)

and $$k_2 = 0.075 - 2.0\left(\frac{B}{D}\right)^{-1}\left(\frac{qB}{EA}\right)^{-0.2}$$

(5.8)

$$\frac{y_{max}}{B} = 0.23\left(\frac{B}{D}\right)^{0.76}\left(\frac{qB}{EA}\right)^{0.54}\left(\frac{p}{q}\right)^{k_3}\left(\frac{f}{p}\right)^{-0.15}$$

(5.9)

$$k_3 = -0.6 - 0.5\left(\frac{B}{D}\right)^{-1}\left(\frac{qB}{EA}\right)^{-0.37}$$

(5.10)

Y_{max}=15.789 m

σ_t=343 MPa

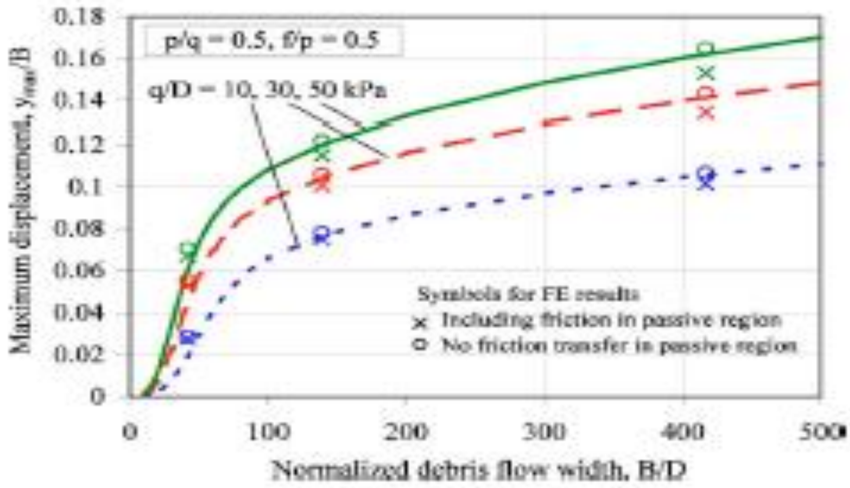


Figure 5.13 Summarized chart of deflections using the suggested numerical model[Randolph et al.,2010]

6. Parametric Analysis

In this chapter, we will show the results of our parametric study. Examining different range of outside diameter (D_o), length of landslide (B) and different values for active and passive zones loading (q,p,f), we will indicate the summary graphs in order to highlight the differences of the quantities involved. At this point, we have to clarify that the numerical analyses consist of:

- 3 different values of outside diameter (D)
- 6 different values of slide length (B) (3 at narrow and 3 wide slide case)
- 2 different values of active landslide loading(q), passive resistance loading(p) and frictional resistance(f)

The values used can be considered as the critical cases of pipeline buckling. So, the selection of critical values was made in order to indicate the different behaviors of offshore pipelines under various seismic loads, designing parameters or length of landslides. Certainly, using a Finite Element Method Software, gives the option to try various values of parameters as the solution is easily made. We selected values which can give an examine solution in both methods, analytical and numerical.

At this point, we would like to remind that the inclination of the seabed has not been taken into account neither the angle of landslide loading. Table 6.1 shows the cases as analyzed in ANSYS software.

Table 6.1 Values of all designing parameters as used in numerical study

Designing Parameters	**Values**	
Landslide length, B	Narrow Slides	Wide slides
	B=100	B=200
	B=120	B=250
	B=160	B=300
Outside Diameter, D	D=0.61	
	D=0.72	
	D=0.81	
Normal active, normal and lateral passive resistance loading , q,p,f	p/q=f/p=1/2	
	p/q=f/p=1/3	

6.1. Narrow slides: B/D>200

At this part of the chapter, we will show the results of numerical study for the first case of the analytical solution. The equations, as described in Chapter 4, differ regarding the ratio of landslide length per diameter, B/D. So, we tried to select values that can combine common values of outside diameters and lengths of slides which still keep the ratio B/D<200. In the following tables, we present the values used for the current study.

6.1.1. Check the Range of Diameter, D

In this part, we will show the results of different values of outside diameter. We selected the most common values for offshore pipelines, which are 24', 28' and 32'. Those values are modified in 0.61, 0.72 and 0.81 m each one in SI. The following figures below can indicate the deflection of the pipe of those three different values for B=100 m, B=120 m and B=140 m. Also, we have to clarify that the ratio of loadings is the same with the validated model in all the cases below. (p/q=f/p=1/2)

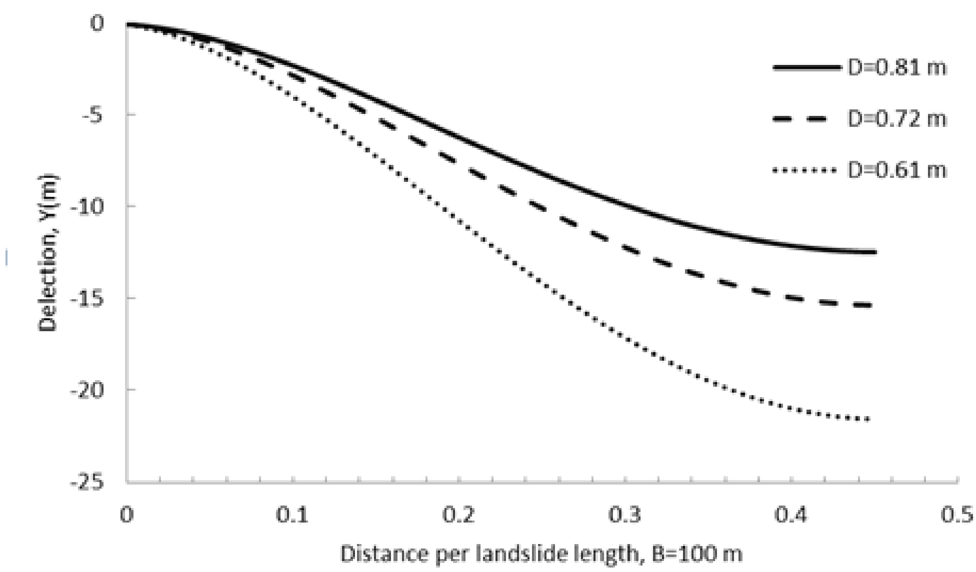


Figure 6.1 Deflection vs. Distance per landslide length, for B=100 m and different values of D

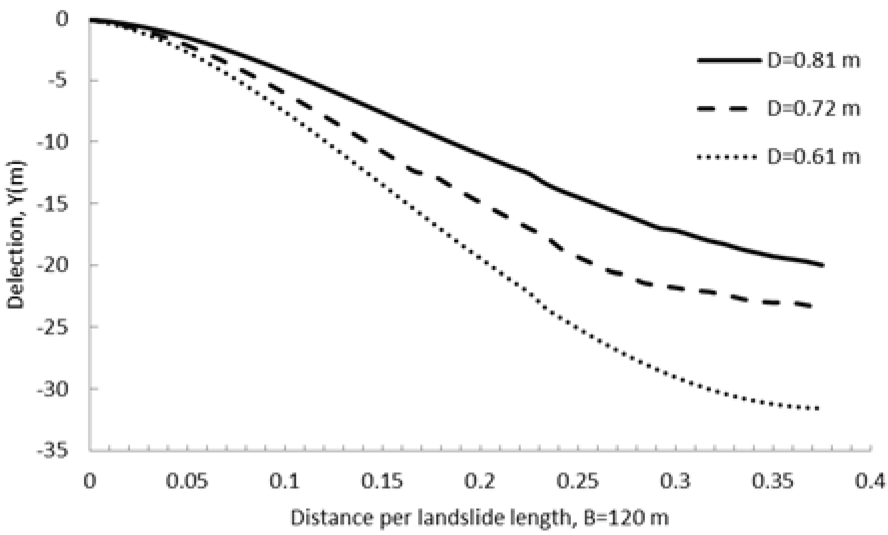


Figure 6.2 Deflection vs. Distance per landslide length, for B=120 m and different values of D

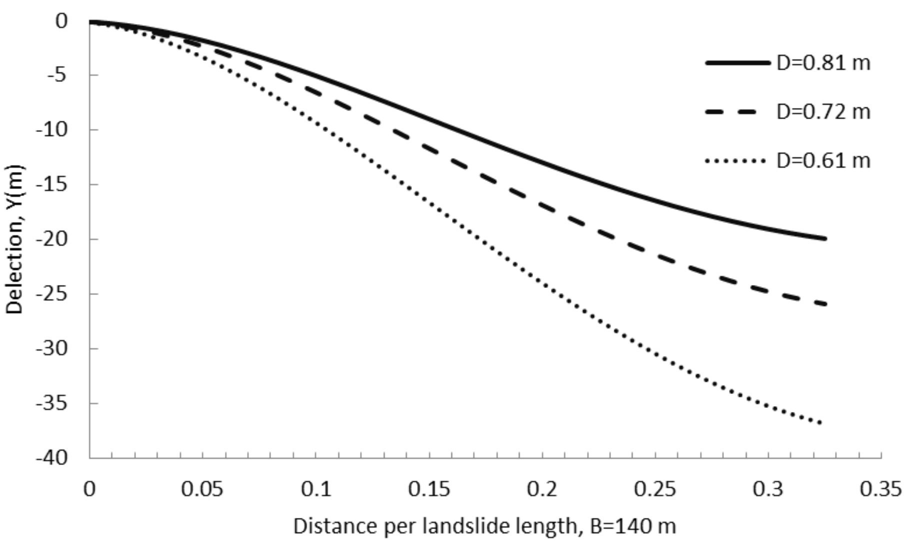


Figure 6.3 Deflection vs. Distance per landslide length, for B=140 m and different values of D

As we can see in figures 6.1, 6.2 and 6.3, the deflection is getting larger when the outside diameter has low values. This indicates that even in the case of landslide length of B=100 m, B=120 m and B=140 m, we expect that the deflection of the pipe with D=0.82m is lower than the pipe with D=0.71m. Moreover, the deflection of D=0.61 m is even lower than that pipe of D=0.72 m in all the three cases.

This is reasonable given that the large diameter makes the pipe a more stable structure and can resist more to the loadings trying to buckle it. We could say that the use of a larger diameter will provide obvious benefits for the project, but this requires an advance application of existing technologies. This is why in offshore industry larger diameters are preferred not only for the advantage of great resistance, but also because of the large amount of liquid they can transfer. In reality, the challenge during installation is highly risky, so the values of smaller diameters are used widely and safely.

Nevertheless, there is an obvious difference in value of the deflection which means that the landslide loading is wider now and the slide presses the pipe more than before. So the deflection in the case of B=100 m the deflection is 21 m and for B=120 m turns to 33 m, for 24' pipe. This indicates the importance of the landslide length, which will be described later on.

6.1.2. Check the range of Landslide Length, B

As it is shown in Table 6.1, we will test three different values of landslide length. We selected the length of 100 m as designed before in order to validate the model used in the study of Randolph et al. (2010). Then we used the length of 120 m and 140 m which still allows us to calculate the deflection using the first case of narrow slides for pipe values 0.81 m and 0.72 m.

However, we observe that the ratio B/D=229 (for values of B=140 m and D=0.61 m) belongs to wide slides and we cannot accurate the results with this form of the analytical solution. So, the Figures 6.4 and 6.5 shows the deflections of the pipe as they calculated with ANSYS software along the length of the pipe.

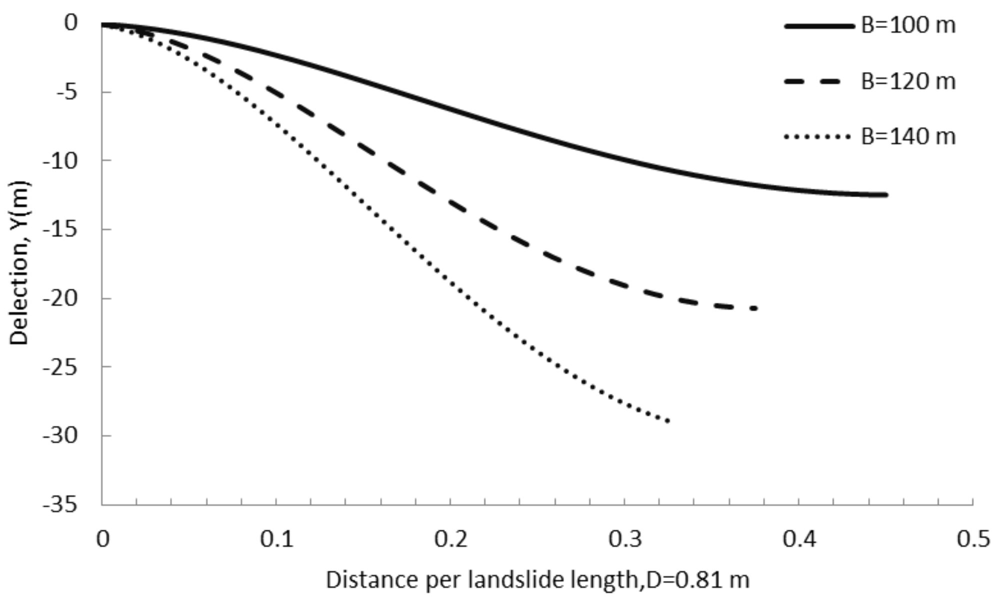


Figure 6.4 Deflection vs. Distance per landslide length, for D=0.81 m and different values of B

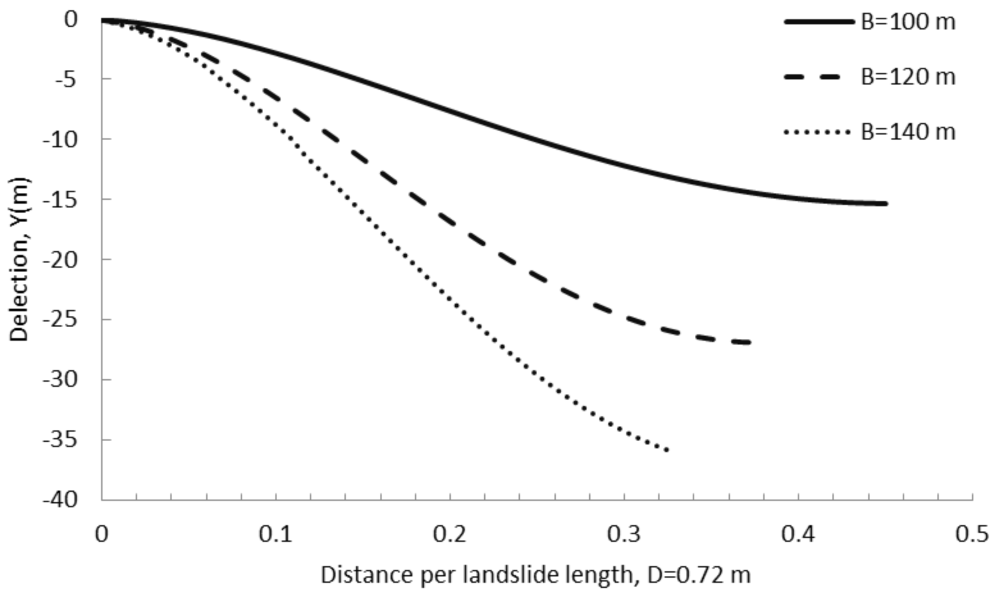


Figure 6.5 Deflection vs. Distance per landslide length, for D=0.72 m and different values of B

As we can assume from the figure, the importance of the landslide length is great to pipeline deflection. We can see the difference of the deflection in these three cases and how larger lengths of slide can provoke larger displacements. For example, in the Figure 6.5, the deflection for a slide 100 m long can provoke maximum displacement of 15.037 m in the middle of the pipe instead of 23.475 m which can be caused by 120 m landslide length. The largest deflections come from 140 m length of landslide which can provoke displacements of 36 m in the middle of the pipe.

Of course, the results are even larger in the Figure 6.5 in comparison with 6.4, as we highlighted before, the parameter of outside diameters affects the results a lot. For the case of the idealized diameter (0.81 m) comes to 35.999 instead of 35.095 in the case of 28' (0.72 m) pipe.

6.1.3. Check the range of loadings in active and passive zones, q, p, f

Now, we would like to test the importance of loadings in active and passive zone. We preferred to use specific values of ratios involved in the analytical equations suggested in the analytical study of Randolph et al (2010). In the first case, we used the values from the validated model (p/q=f/p=1/2) and for the second case we used lower values in passive resistance zone for lateral and normal loading. As a result, the ratio will be equal to 1/3. The following figures indicate the influence of the resistance zone in the pipe.

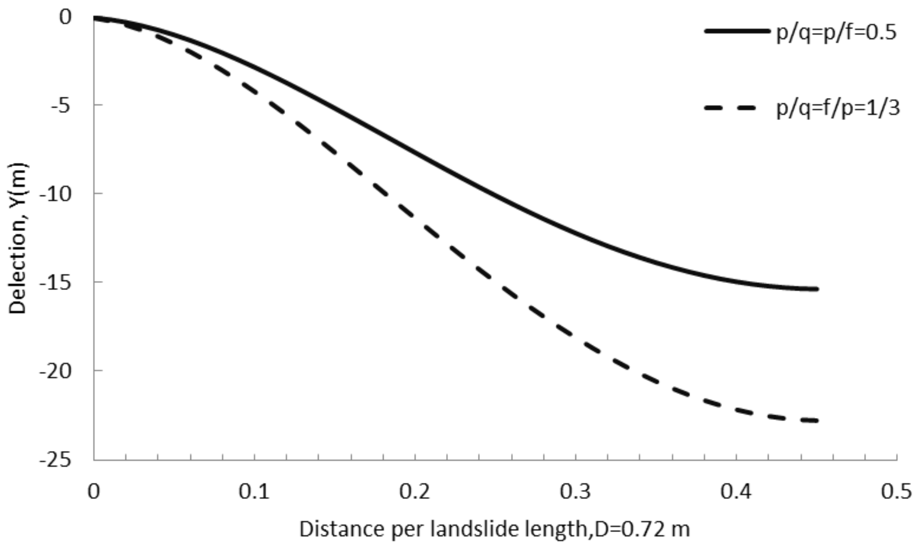


Figure 6.6 Deflection vs. Distance per landslide length, for D=0.72, B=100 m and different values of q,p,f

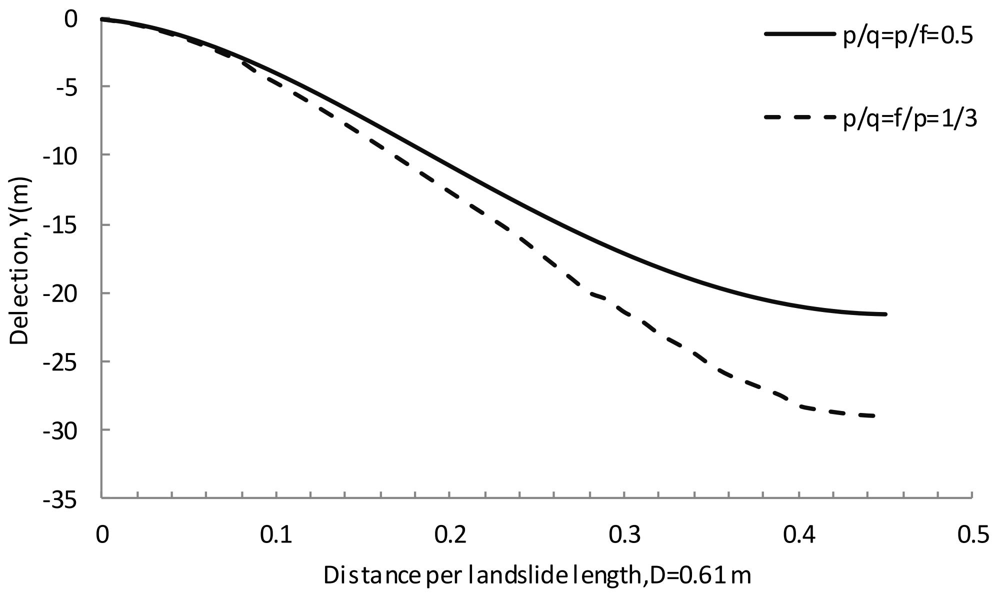


Figure 6.7 Deflection vs. Distance per landslide length, for D=0.61, B=100 m and different values of q,p,f

Judging from the diagrams, the resistance zone functions as a support area when the pipe strains. The passive zone tries to resist to movements of the pipe caused by landslide and remain the structure into its initial shape. So, when this passive zone has lower values, it is reasonable that the pipe cannot resist and avoid the large displacements caused by landslide loading, which actually in our parametric analyses, remains the same.

This is why we have a remarkable difference of the deflections in the Figure 6.7, when the diameter has the lowest value and it is less stable to slide movements. The parametric study used also the analyses of the largest diameter, D=0.81 m, but we selected those examples which indicate more the influence of low value sin passive zone loadings.

6.1.4. Verification with analytical solution

This part can verify the results of our parametric study and can indicate that we should use safely either the analytical solution or the numerical study using the finite -element method to calculate the deflection of the pipe in an initial stage. Of course, there are some idealizations and limitations, as described before, which simplify the model. We should study further more complex problems which include the inclination of loadings or the initial tension of the pipe.

The benefit from this method is that we can easily modify the necessary parameters of the pipe, such as the value of diameter, the wall thickness, the Young's Modulus or the nonlinear behavior of soil characteristics with ANSYS software. In such an approachable way, we should also change the values of the analytical solution using Microsoft Excel which is useful for industry purposes.

In the following Table we can see the results from the analytical solution for all the analyses regarding the narrow slides. The red written values do not belong to narrow slides case, so we did not calculate the deflection

Table 6.2 Results of Parametric Study of Numerical and Analytical Solution

B	D	B/D	q(kN/m)	p(kN/m)	f(kN/m)	q/D	E(Gpa)	A	t	qB/EA	k3	ymax/B	ymax anal	ymax ansys
100	0.72	138.8889	21.6	10.8	5.4	30	210	0.062954375	0.029	0.000163383629	-0.69066	0.157889	15.968	15.369
120	0.72	166.6667	21.6	10.8	5.4	30		0.062538303	0.0288	0.000197364761	-0.67045	0.198042	23.76508	23.472
140	0.72	194.4444	21.6	10.8	5.4	30		0.062538303	0.0288	0.000230258888	-0.67974	0.243548	34.09678	35.999
100	0.81	123.4568	21.6	10.8	5.4	26.66667		0.079150039	0.0324	0.000129952106	-0.71101	0.129393	12.93932	12.476
120	0.81	148.1481	21.6	10.8	5.4	26.66667		0.079150039	0.0324	0.000155942527	-0.68647	0.161236	19.34828	19.818
140	0.81	172.8395	21.6	10.8	5.4	26.66667		0.079150039	0.0324	0.000181932948	-0.67001	0.194776	27.26869	27.913
100	0.61	163.9344	21.6	10.8	5.4	35.40984		0.044889086	0.0244	0.000229136191	-0.66777	0.211594	21.15935	21.573
120	0.61	196.7213	21.6	10.8	5.4	35.40984		0.044889086	0.0244	0.000274963429	-0.65279	0.265417	31.85003	30.919
140	0.61	229.5082	21.6	10.8	5.4	35.40984								
100	0.72	138.8889	21.6	7.2	2.4	30		0.062538303	0.0288	0.000164470634	-0.69044	0.222758	22.27581	22.183
120	0.72	166.6667	21.6	7.2	5.4	30		0.062538303	0.0288	0.000197364761	-0.67045	0.244571	29.34849	28.999

140	0.72	194.4444	21.6	7.2	2.4	30		0.062538303	0.0288	0.000230258888	-0.65704	0.332555	46.55772	48.014
100	0.81	123.4568	21.6	7.2	2.4	26.66667		0.079150039	0.0324	0.000129952106	-0.71101	0.183454	18.34542	18.167
120	0.81	148.1481	21.6	7.2	2.4	26.66667		0.079150039	0.0324	0.000155943	-0.68647	0.226338	27.1605	27.196
140	0.81	172.8395	21.6	7.2	2.4	26.66667		0.079150039	0.0324	0.000181933	-0.67001	0.271602	38.02427	37.702
100	0.61	163.9344	21.6	7.2	2.4	35.40984		0.044889086	0.0244	0.000229136	-0.66777	0.294785	29.47849	29.757
120	0.61	196.7213	21.6	7.2	2.4	35.40984		0.044889086	0.0244	0.000274963	-0.65279	0.367531	44.10368	42.874
140	0.61	229.5082	21.6	7.2	2.4	35.40984								

6.2. Wide slides: B/D>200

For the second part of analyses, we check the widths of landslides B/D>200m. So the parametric study has the similar process. At the end of the chapter, we will show the results from the analytical solution in order to compare them.

6.2.1. Range of Design Parameters (Diameter, landslide Length and Loadings)

A similar procedure has been occurred in the case of wide slides as described before. We conducted numerical analyses using different values of landslide length, diameter and loadings which validate the second case of analytical solution. We thought that instead of changing the length of landslide, which makes a totally different geometry model of the pipe, we could change only the value of diameter in order to have the same result of ratio B/D.

For example, for the case of landslide length B=250 m and D=0.72m, the ratio involved in the analytical solution is 250/0.72=347.22>200(case of wide slides). So, we could keep the geometry model of 100 m long slide and decreasing the diameter into the specific value which gives us the same ratio result (100/0.288=347.22), we could easily get the same result of the numerical analysis.

Before applying such a method to our numerical study, we verified it using analyses from the previous geometry models where the landslide length was different and we checked the results. After securing that our method figures out to correct results, then we conducted the second part of analyses and verified the results with the analytical solution.

- *Range of Diameter*

In the Graph 6.8, we conclude that the larger the diameter is, the deflection has lower values. We show this example of B=250 m with ratio loading p/q=f/p=1/2. We can see that the displacements in the case of 24' pipe (0.61 m) can be double in comparison with 28' pipe (0.72 m).

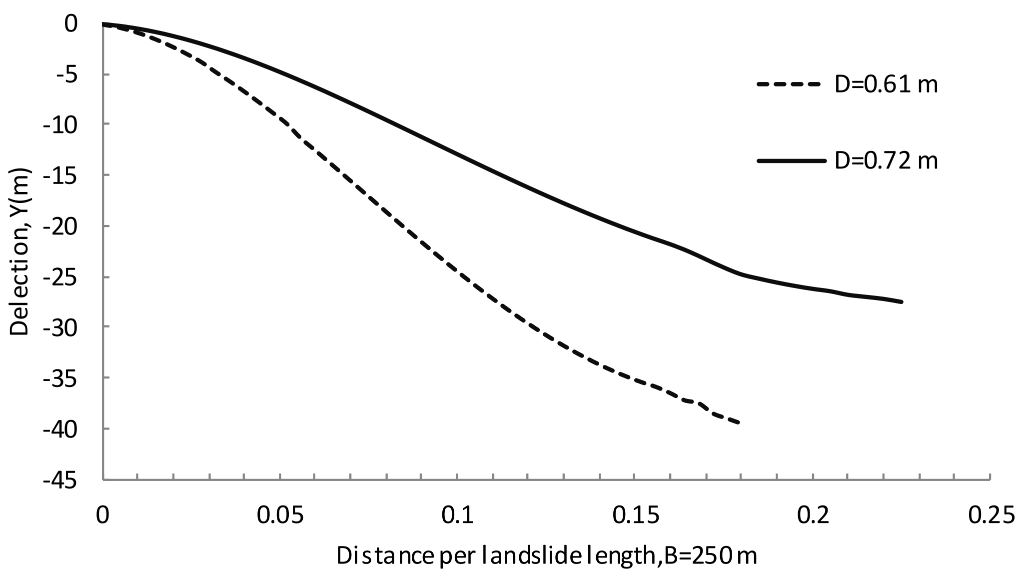


Figure 6.8 Deflection vs. Distance per landslide length, for B=250 m and different range of D

- *Range of Landslide Length*

In the Figure 6.9, we selected to show some of the results of our parametric study in order to confirm again the importance of landslide length. In that case , the slide is either 200, 250 or 300 m long so the pipe strains in a wider area than the previous examples. We would like to remind that in section 6.2 we analyze the case of wide slides that is why we select much more larger lengths of slides.

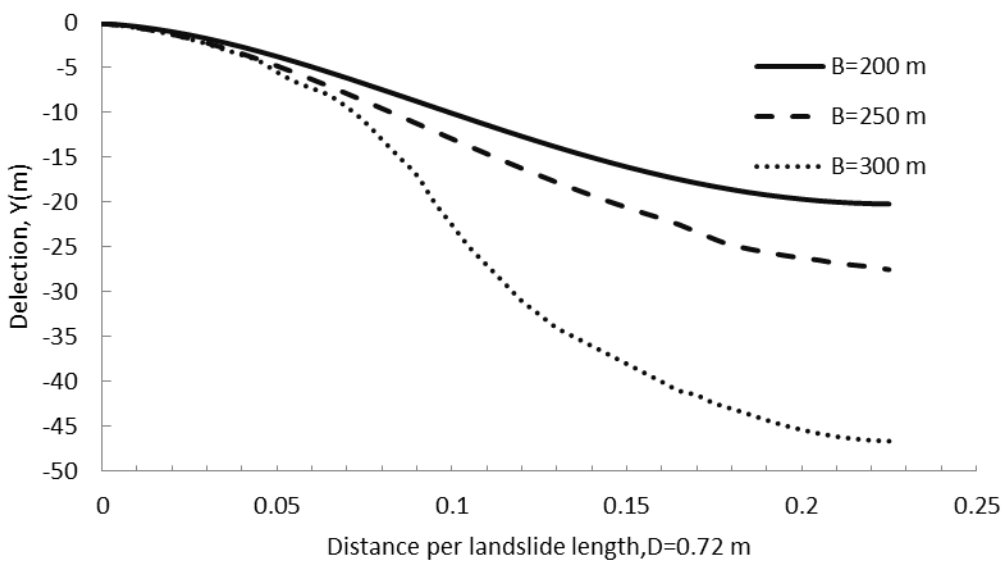


Figure 6.9 Deflection vs. Distance per landslide length, for D=0.72 m and different range of B

From the diagram above, we can see the great difference of the deflection when the slide is 300 m long, where we can observe the largest displacements of the pipe(approximately 45 m).We would like to clarify that such an important deflection may be studied further using a more accurate method. In offshore industry, the maintenance and repair works are not easily approachable as in onshore environment. Also, that means a great loss of financial benefit for the oil and gas industry so we should be careful to areas where seismic evenest can be occurred.

- *Range of loadings in passive zone*

The last step of these analyses is to test the importance of ratios of active and passive loadings. In these analyses we used two options: p/q=q/f=0.5 or 1/3. We selected again a graph came from landslide length 300 m, of 32' pipe(0.81 m), which provokes great displacements. The difference between those two cases is so obvious, as the largest deflection reaches to 67 m approximately. For those cases too, a detailed and more accurate study is needed in order to prevent the damages which can affect the function of the pipe.

After the parametric study, we will show the results of the analytical solution in order to be easily compared. The results seem similar with two methods and that was the great achievement of this current thesis; finding a linear solution which can give us accurate results for the initial study of an offshore pipeline and vice versa.

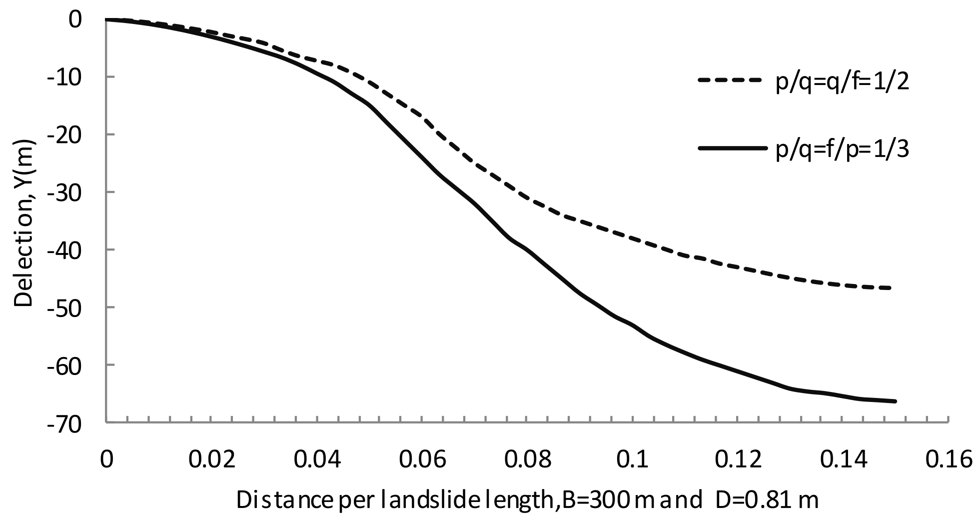


Figure 6.10 Range of q, p, f for B=300 m and D=0.81m

6.2.2. Comparison with the analytical solution

As we validated the results of the numerical study before, we would like to show the comparison between the two methods in this case too. The differences are lower between the analytical and numerical method, which seems that the equation for wide slides is more accurate. In the following Table we can see the results and compare them for all the combinations of designing parameters.

Table 6.3 Validation of analytic al solution for wide slides

B	D	B/D	q(kN/m)	p(kN/m)	f(kN/m)	q/D	E(Gpa)	A	t	qB/EA	k2	σt/E	ymax/B	ymax analytical	ymax ansys
140	0.61	229.508	21.600	10.800	5.400	35.410		0.045	0.024	0.000	0.031	0.001	0.141926	19.86968	20.325
140	0.61	229.508	21.600	7.200	2.400	35.410		0.045	0.024	0.000	0.031	0.001	0.209546	29.33646	29.087
200	0.72	277.778	21.600	10.800	5.400	30.000	210.000	0.063	0.029	0.000	0.039	0.001	0.141547	20.26589	20.654
250	0.72	347.222	7.200	3.600	1.800	10.000		0.063	0.029	0.000	0.041	0.000	0.111966	27.99152	27.315
300	0.72	416.667	21.600	10.800	5.400	30.000		0.063	0.029	0.000	0.053	0.001	0.153416	46.02473	46.879
200	0.81	246.914	7.200	3.600	1.800	8.889		0.079	0.032	0.000	0.022	0.000	0.101118	20.22351	20.004
250	0.81	308.642	21.600	10.800	2.300	26.667		0.079	0.032	0.000	0.043	0.001	0.169325	42.33128	42.854
300	0.81	370.370	21.600	7.000	2.300	26.667		0.079	0.032	0.000	0.049	0.001	0.222045	66.61343	67.025
200	0.61	327.869	21.600	7.000	2.300	35.410		0.045	0.024	0.000	0.047	0.001	0.232689	46.53778	46.214
250	0.61	409.836	21.600	10.800	5.400	35.410		0.045	0.024	0.001	0.053	0.001	0.159478	39.86962	40.019
300	0.61	491.803	21.600	10.800	5.400	35.410		0.045	0.024	0.001	0.058	0.002	0.165137	49.541	50.123

7. Conclusions and Further Study

The last chapter suggests some additional thoughts for further academic ideas and includes also the conclusions derived from the parametric study. The target of this academic study is to collect a summarized guide about the behavior and response of offshore pipelines under landslide loading.

It cannot be characterized as an extensive research study focusing on all different aspects and parameters involved in subsea engineering and seismic design. However, it is an initial stage how we can investigate a case like that and different approaches which have been already suggested by specialized researchers.

The conclusions derived from the current study are how the designing parameters can affect the response of an offshore pipeline under static loading. Certainly, this problem has been idealized in order to predict the displacements using an easy approach, which has been validated.

In general, the influence of outside diameter is a great issue. In offshore industry it is a great challenge to install large offshore pipelines and the academic interest comes to this purpose. So, we understood that having a large diameter can protect the operation of an offshore pipeline under static loads. The deflection and the strains are much lower than the ones observed on pipelines with smaller diameter.

The other important factor analyzed in this thesis is the length of the landslide. The length of landslides can increase or decrease the loading of the pipe along the offshore pipeline, which is the main reason of stresses. As a result, a wider area under loading can provoke larger displacements in the pipeline in comparison with a smaller one.

The last parameter studied is the loadings in active and passive zones of the pipe. Using the analytical solution in order to validate the numerical results, we did not change the values of landslide loadings as we wanted to check the ratio of loadings of active zone divided to passive zone. At the end, we figured out that low values of passive zone can cause larger permanent displacements into the pipeline.

For future academic projects, many other parameters can be tested further. The inclination of landslides varied from 0-10 degrees are another issue which can affect the loadings and as a result the behavior of the pipeline. Also, the inclination of the seabed is another factor we could take into account. Different material behavior may be influence the response of the pipeline in a different way. As it is a new and interesting topic which will be relevant to future projects at least in Mediterranean, the motivations for further study are high from the oil and gas contractors and researchers too.

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