

THEORY AND PRACTICE OF
DEEPWATER PIPE LAYING.

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Theory and Practice of Deepwater Pipe Laying

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Summary/Introduction

Actual offshore developments (steel platforms and subsea completions in up to 1025 ft. of water), the world energy situation, and continued increase in proven and probable oil and gas reserves in deep water suggest a boom in construction of submarine pipelines in over 600 ft. water depth. Human accomplishments frequently have been developed out of practice and years of experience, leaving for a later stage the theoretical aspects, which then are used as a help to get better understanding and improvement of these achievements.

Installation and operation of submarine pipelines may be an example.

Until now, any disaccord or lack of correlation between theory and practice might not show practical or relevant implications. However, as indicated by theoretical studies and some laboratory results, future installation of submarine pipelines in deeper waters than the present construction boundaries will require a close conformity between theory and practice. Some areas of concern may be the following:

- 3-dimensional analysis of suspended pipelines from lay barges
- collapse and buckling phenomena
- non-linearity behaviour of pipelines
- short and long term design data related to environmental conditions
- sea bottom configuration and soils
- second-end connection problems
- correct interpretation of Archimedes' Principle
- etc.

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For example, in theoretical analysis of suspended pipelines from a barge, the application of Archimedes' Principle has been frequently misused. In practice, for less than 600 ft. water depth, such probable misconception does not show relevant implications. However, its proper interpretation and correct reproduction is of foremost importance in the study of the buckling phenomena during installation of submarine pipelines, in the pipeline design, and in the preparation of realistic construction procedures.

Relevant preliminary results have been already published by Protech International. Furthermore, since 1978, in co-operation with Delft University and other Dutch institutions, a research program is underway to analyse the buckling and collapse phenomena which might occur during the installation of submarine pipelines. The proper reproduction of the phenomena is done using a special apparatus developed by Protech International. At the Energy Sources Technology Conference, February 1980 in Louisiana, USA Mr. I. Konuk of Protech International will be presenting the paper "Higher Order Approximation in Stress Analysis of Submarine Pipelines". Even with recent progress in numerical solution techniques the majority of the known works specialise in two-dimensional problems with limited applications, either to water depths or pipe characteristics. In this paper is presented an unified three-dimensional non-linear formulation of submarine pipelines or riser problems developed by following the rod theories.

Sometimes theory arrives before practice, as is the case for the solution of second-end connection problems. So far, theoretical and laboratory studies have been the only alternative to optimise the submarine pipe length and prepare operational construction procedures prior to the completion of second-end connection problems. The basis for the completion of the first second-end connection project using steel pipelines and automated connection, in a commercial oil field are the theoretical and laboratory studies. There are several advantages to using the second-end connection technique, and we can expect a rapidly increase of its application in installation of flowlines for subsea completions and pipelines in deep water.

Suspended Pipeline during Installation by the Laybarge Method

In the analysis of a suspended pipeline the boundary conditions are sensitive factors to be taken into consideration for each particular pipeline, for example: sea and weather conditions; barge configuration and response; stinger type and geometry; available tension at the barge; soil properties and configuration of the sea bottom; location, water depths and length of the pipeline.

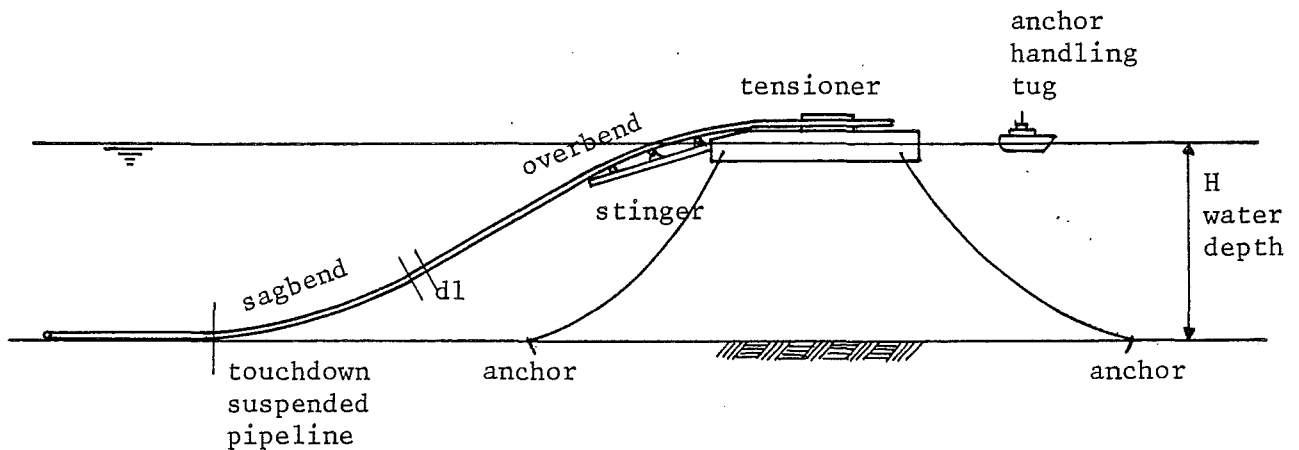
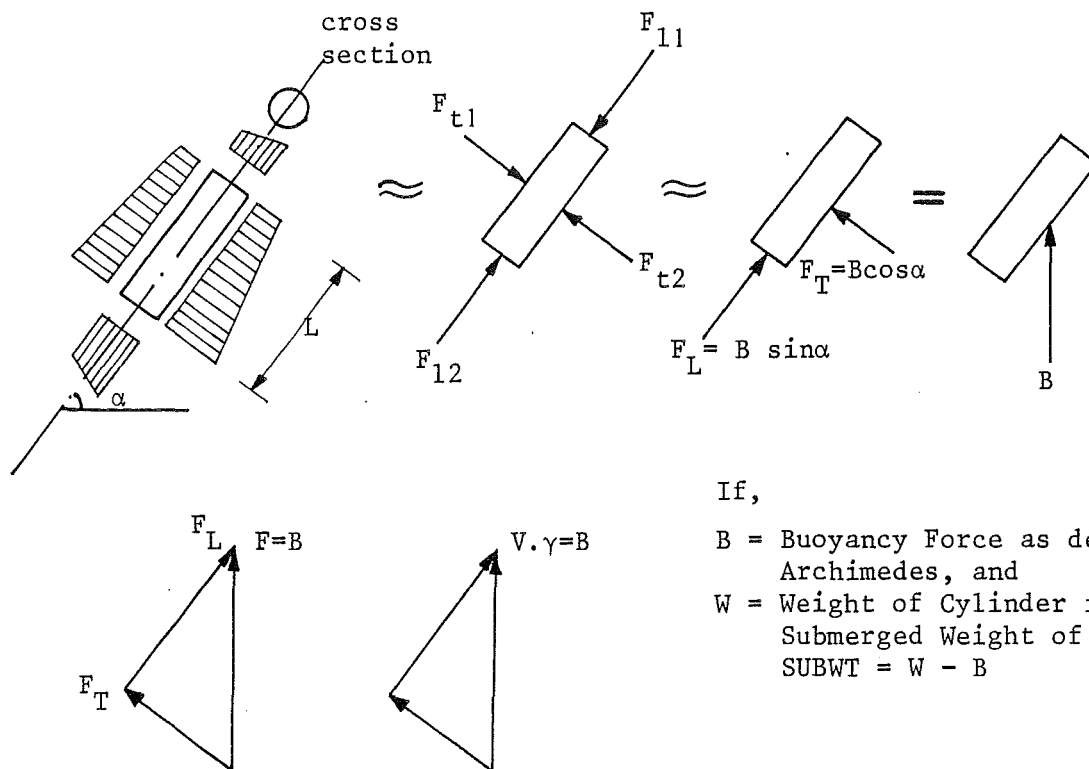


figure 1. Schematic representation of typical pipeline installation by the laybarge method

The basis for the theorization of the suspended pipeline are the physical properties of the pipe and the boundary conditions during installation. This relationship may be broken, if considering, the submerged weight of the suspended pipeline accordingly tot the Archimedes' Principle, which states: "The apparent loss in weight of a body totally or partially immersed in a liquid is equal to the weight of the liquid displaced". Submarines pipelines installed by the laybarge method are layed empty (i.e. air filled); without a resultant of hydrostatic pressure along the axis of the pipeline. The hydrostatic pressure around the pipe provides a resultant force perpendicular to the axis of the pipe. For the suspended pipeline, the buoyancy as defined by Archimedes' Principle demands of both hydrostatic components of force, as it is shown on figure 2, idealized for the case of a cylinder submerged in a liquid.

Hence the concept of submerged weight by a misuse of Archimedes' Principle is not valid for the suspended pipeline during installation by the lay-barge method.



If,
 B = Buoyancy Force as defined by Archimedes, and
 W = Weight of Cylinder in Air, then
 Submerged Weight of Cylinder:
 $SUBWT = W - B$

Where:

- A = Cross Section Area
- V = Cylinder Volume
- L = Cylinder Length
- α = Angle to the horizontal
- γ = Liquid Specific Weight

figure 2. Forces acting on a cylinder submerged in a liquid. Archimedes' Principle.

Variations in sea bottom and/or laying sequence and logistic might introduce different answers or results in the suspended pipeline. Other important boundary conditions, normally, does not change during the installation or construction period, such that, more attention may be focus to the mentioned variations.

The geometry and forces acting on the suspended pipeline are obtained from the correct reproduction of the phenomena, proper formulation of the problem and the solution of the equilibrium equations derived from the forces acting on an element, along the suspended pipeline, and its boundary conditions (see figure 3).

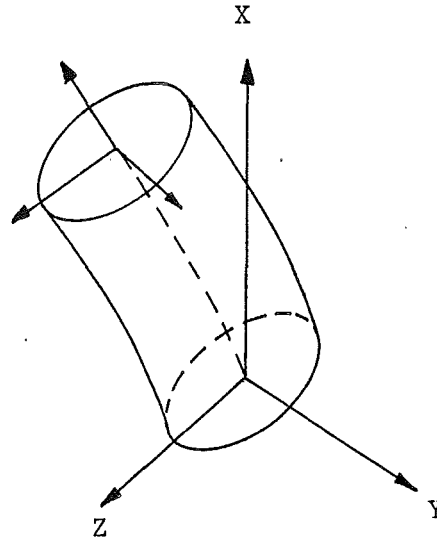


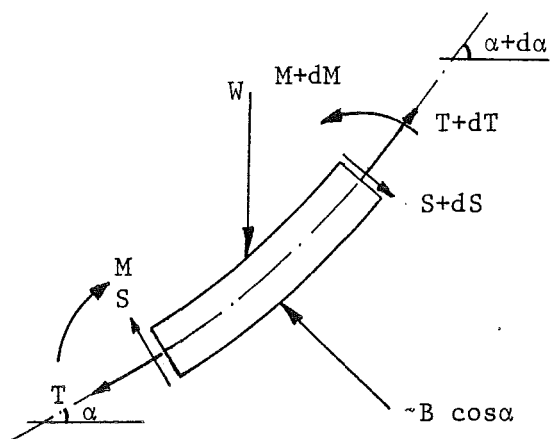
figure 3. Element "S" of the suspended pipeline
orthogonal co-ordinate system

The general equation derived from the equilibrium equations of forces and moments acting on an element "S" of the suspended pipeline may be written as follows:

$$\frac{D \underline{U}}{DS} + J \underline{U} + \underline{G} = 0 \tag{1}$$

Where, the vectors \underline{U} and \underline{G} denote the generalized internal and external forces respectively; the matrix J specify the rotation of a moving co-ordinate system including the geometric torsion and curvature of the pipe axis on the XZ, XY planes respectively. The $\frac{D}{DS}$ denotes differentiation of components in a moving system.

The two dimensional forces acting on an element "dl" of the suspended pipeline, neglecting the effect of water current velocities are shown on figure 4, as follows:



Nomenclature:

- M = Bending Moment
- T = Axial Force (Compression/Tension)
- S = Shear Force
- B = Buoyancy Force (Archimedes)
- W = Weight of element 'dl' in air
- \$\alpha\$ = Angle to the horizontal
- dl = Length of element

figure 4. 2D Forces acting on element 'dl' of the suspended pipeline

Summarised remarks in regards to the suspended pipeline and Archimedes' Principle are the following:

1. The known concept of Archimedes' Principle is not valid for the suspended pipeline because the force '\$B \sin \alpha\$' does not exist, there is not pressure due to water, there is only air at the atmospheric pressure. This missing resultant of external pressure along the pipeline axis is required to fulfil Archimedes' buoyancy and submerged weight concepts, as it is shown on figures 2 and 4.
2. For a water depth 'H', the missing value of water pressure integrated along the suspended pipeline gives a resultant force at the water surface equal to:

$$\int_0^H B \cdot \sin \alpha \cdot dl = B \cdot H \quad (2)$$

Where 'B' is the pipe buoyancy force per unit length.

For most laying conditions and present tension equipment in deep water imply a resultant axial tension force in the upper part of the suspended pipeline and a resultant axial compression force in the lower part. Important when studying the buckling phenomena, see figure 4.

As reference, for 2000 ft. water depth with 24" and 36" O.D. suspended pipelines during installation, the missing axial forces at the water surface given by equation 2 are about 200 and 450 Tons respectively.

3. Up to the present depths of installation of submarine pipelines by the laybarge and under normal circumstances, it has been possible to obtain acceptable design stresses and the correct geometry of the suspended pipeline by using the pipe submerged weight accordingly to Archimedes' Principle. That is possible, if neglecting axial deformation, then the geometry of the suspended pipe in water is exactly the same as that of similar pipe in air, except that its theoretical weight in air is equal to the submerged weight as defined by Archimedes' Principle. In this later assumed model, there is not water pressure, in addition the obtained axial forces of this solution must be corrected accordingly.

The geometry of the suspended pipeline is determined for a perfectly round pipe, however pipes are not perfectly round.

Therefore, to forecast the total combined stresses in the suspended pipeline is required to consider the following: probable initial out of roundness in the pipe, stresses due to water depths, moments, axial and transverse forces.

Similar considerations are required in the study, reproduction and prevention of the buckling and collapse phenomena. Hence, to establish successful installation procedures and pipeline design is of foremost importance to understand properly the suspended pipeline phenomena and its boundary conditions.

4. The knowledge of some phenomena in submarine pipelines is mostly based on experimental results from prototype and physical models, e.g. fatigue, corrosion and buckling. The study, propagation and prevention of buckling in submarine pipelines must be based on results from the proper reproduction of the laying conditions. From there, the pipe wall thickness design can be checked and arresters may be designed to prevent buckling propagation.

Frequently studies on this matter have not reproduced properly the suspended pipeline phenomena in deep water. As it has been described, see figures 1 and 4, expected conditions favourable for possible buckling initiation and/or propagation in deep water may occur at the sagbend, near the sea bottom, probable with the suspended pipe under elastic bending moments, an axial compression force and the pipe with initial out of roundness.

Certainly, there are several other combinations and extreme conditions that might initiate a buckle.

In the near future we can expect better understanding on the combine effects of axial compression forces, bending moments and external pressure to prevent buckling initiation for submarine pipelines in depth water. See figure 5.

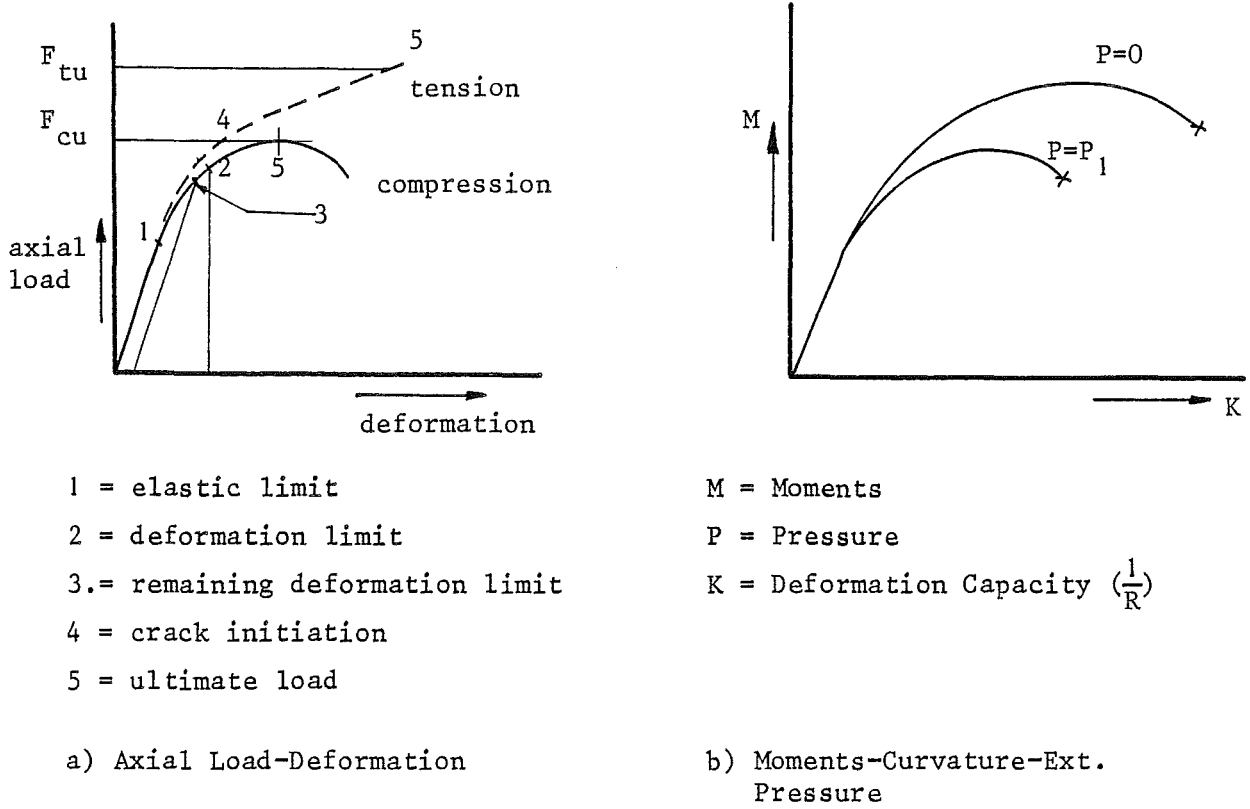


figure 5. Criteria of failure and collapse in pipelines

Second-end connection

The second-end connection method can be used with single or bundle steel pipelines for relatively short distance separation between two submarine structures (e.g. wellhead, platform, SPM, Subsea Cloister-Manifold Center, etc.). No adjustments are required in the pipeline length or in the connection points position. Furthermore, there is a saving in time with relation to traditional connection methods, increased by using automated connectors, probably diverless and no spool-pieces. In principle, the method is suitable for any waterdepth. However, more application of this method can be expected for deep water, subsea completions and marginal fields.

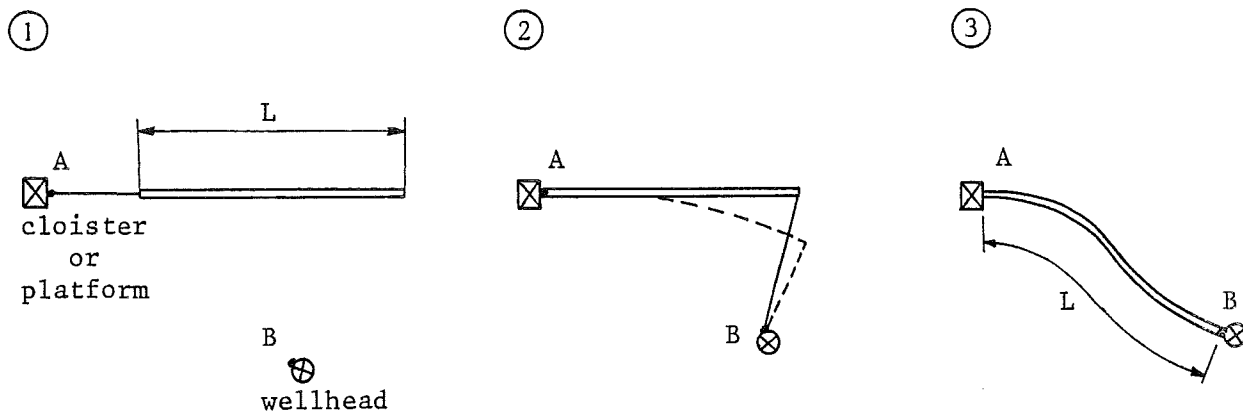
The development of the second-end connection is based on both, practical and theoretical aspects. The correct physical boundary conditions are of foremost importance for the mathematical solution, similarly, a good understanding of this solution is the basis of the installation procedures and efficient utilization of available construction equipment and techniques.

From a theoretical point of view the design problems can be reduced to optimize the pipeline length: firstly, to perform the end connections without spool-pieces or adjustments to pipelength or connection points; secondly, to design a safe system without overstressing the pipeline, either during installation or operational conditions.

To fulfil these conditions is essential to keep in mind the following practical aspects:

- a. Degree of accuracy in the obtainment of sea bottom configuration, soil properties and variations, and orientation-coordinates of connection points.
- b. External pressure and measurement/forecast of environmental forces, both during installation and operational conditions.
- c. From second-end connection theoretical results, achievement of an acceptable bending moment distribution, with a stable and less sensitive pipeline geometry in regards to installation techniques, experience and available equipment.
- d. With obtained geometry, after second-end connection, check operational stresses for expected pipe restrains, internal pressures, and thermal expansion due to temperature variations. The stresses induced in the pipeline should not exceed the allowable limits after operational stresses are included.

A plan view representation of the second-end connection is shown on figure 6. The transport of the pipeline to the installation place may be done by a version of the bottom tow technique. Probably to reduce friction forces and facilitate the submarine connections, the pipeline system may be suspended off the sea bottom and held back to the sea floor by chains weight.



- a. Pipeline at location with rigging for first end connection
- b. First end connection with rigging for second end connection
- c. Second-end connection

figure 6. Second-end connection, plan view

Change of rigging for tow-in and first end connection have been performed on different occasions. Hence, the rigging to start the second-end connection should not give any difficulty. At this stage start the second-end connection: Pipe in point A is clamped, orientations at A and B are known and fixed; by utilizing a single cable the final installation of this pipeline will be possible by using a side deflection, as illustrated on figure 6.

The design and installation problem has been further reduced to the following:

1. To fit a pipelength 'L' between points 'A' and 'B' and having directions θ_a and θ_b respectively. In principle the shape of this curve may be S, U or Ω . See figure 6c.
2. This geometry should fulfill allowable stress limits due to installation and operational conditions.
3. Due to installation conditions, in clamp point 'B' must be a tension force and probably no bending moments may be allow at this point. If these conditions are maintained, then the shape of the pipe geometry must be a 'U', as it will be discussed. No 'S' or ' Ω ' curve is feasible unless a counter moment and/or compressive force is applied at the clamp end 'B'. See table 1.

The general formulation of this problem may be represented by equation (1). However, to obtain a general qualitative analysis of the problem, the equilibrium equations may be simplified, as follows:

Friction forces have been temporarily neglected and sea floor has been assumed horizontal and flat. Then, the solution may be expressed in terms of the following resultant equation:

$$s(\theta) = (\epsilon/2)^{\frac{1}{2}} \int_0^{\theta(s)} \frac{d\theta}{(K - \delta \cdot \cos \theta - \sin \theta)^{\frac{1}{2}}} \quad (3)$$

where: θ = angle of tangent with respects to an X-axis at point s
 s = length of pipe at θ
 ϵ = pipe stiffness parameter, constant
 δ = axial and shear force parameter, known
 K = gravitational constant

It is possible then to predict the behaviour of solutions for this type of equation by drawing the phase diagrams.

The following table illustrates possible pipeline configurations based on above elliptical integral. This is a helpful application of theoretical analysis in the design and operational procedures of second-end connection problems.

CASE	FORCE CONFIGURATION	BENDING MOMENT CONFIGURATION					
		1		2		3	
IA		U		U		S	
IB		U		Ω or U		S	
IIA		U + U		U + U		S + U	
IIB		U		Ω or U		S	
PIPE CONFIGURATION							

Table 1. Possible pipe configurations