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Development of Towing Techniques for Deep Water Flowlines and Risers

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Abstract
The interest of towing techniques for the installation of flowlines and risers has greatly increased in recent years, particularly for deep-water field developments. Surface tow presents particular interest although it is more delicate to engineer compared to other tow methods. This paper presents experimental data and feed back from surface towing trial operation performed by Acergy. Numerical models of tow operation can now be developed through dedicated software to allow engineers to better assess the behavior of the pipeline. During the Girassol project the limitations identified by engineering analysis were compared with data collected on field during operations to further improve the knowledge of the tow method and propose innovative and competitive alternatives to existing methods. A new surface towing technique adapted for long pipeline is presented which uses a wave configuration (patent pending). The paper also identifies the limits of application of the surface wave tow method in terms of pipe diameter, flowline length, environmental conditions, etc. The fabrication and overall costing aspects are addressed and compared with other pipe laying techniques.

Introduction
For the last three decades, the towing techniques have been used for large diameter carrier pipe denoted as bundles (including production lines, service lines, umbilicals etc.) on field development with constraining flow assurance requirements /1/2/3/4/. In recent years, the interest of towing techniques for the installation of flowline and risers has greatly increased, particularly for deep-water field development. Basically the reasons for selecting a tow method as opposed to a conventional laying ship or barge is due to:

- either fabrication requirements where the pipe cross section consists of the use of a bundle design,
- or economic reasons in the case the field development location is remote and the installation scope does not justify the mobilisation of a conventional laying spread /5/.

Deep water field development requires the utilisation of a dedicated installation spread designed to cope with the high tensions and the large amount of permanent work to be transported and installed. This represents a substantial investment for the contractor and the utilisation of such spreads also has to be shared between several regional markets. As a result projects developing deep-water fields in remote areas generally account for high mobilisation cost to bring appropriate installation spread in the region. Also there are increasing number of subsea fields with shorter flowlines (less than 20km) making the use of towed pipelines more attractive. Other positive issues include: the recent developments in engineering software and design codes allows better evaluation of pipe behavior and fatigue damage evaluation; recent deepwater operations allow to reduce and manage the risks successfully and effectively, and high performance DP tugs are available world wide. Therefore the deep water and ultra deep water market and associated constrains and recent technology development provide the motivation to revisit towing installation techniques which have a high local content as an alternative to more conventional installation techniques.

The development of the Girassol field (bundled riser and production flowlines) /1/ has proved that towing techniques were still technically and commercially competitive compared to conventional surface transportation and installation spread even in a deep water environment. The successful installation of the Hyperflow Riser Towers and production bundles at the Girassol field, combined with the results of experimental data from the early sixties, motivated the Acergy engineering team to further improve the knowledge of the tow method and propose innovative and competitive alternatives to existing methods. Acergy developed a new surface towing technique (patent pending), which uses a wave configuration and allows a better and more flexible control of the line during the tow. The fabrication and overall aspects are addressed and compared with other pipe laying techniques.

Surface tow through an experimental approach.
The behavior of the pipe when floating on surface of an ocean is difficult to model accurately without the assistance of sophisticated software operated from high performance computer. Those softwares did not exist in the sixties when the first surface towing operations were considered for pipeline installation. At the time engineers had to perform trials to

[1] Previously Stolt Offshore

confirm the stress level and fatigue damage generated by action of the surface sea motion.

Acergy performed or participated, from 1960 to 1975 in a series of full-scaled tests aiming at better understanding the effect surface towing operation on a pipe.

The deep water tow operation for Saharan Natural Gas (1960-1962).

The Saharan project aimed to lay a gas export pipeline across the Mediterranean Sea between Mostaganem in Algeria and Cartagena in Spain. Due to the water depth (2500m) and the length of the laying route (70km), this project was extremely challenging at the 1960s. (**Figure 1**).

A fabrication yard was set up at the location of Djebel Diss and the testing program covered the following operation to validate the method:

1. Launching of pipe stalks from fabrication facilities to shallow water.
2. Towing from shallow water to site and upending of first end.
3. Surface tie-in connection between two pipeline sections (**Figure 2** and **Figure 3**).
4. Laying and control of the pipe along a curved route.
5. Controlling and descending of the pipeline with the adjustable buoyancy elements.
6. Reversibility of the laying operation.

The submerged weight of the pipeline with buoyancy module attached was adjusted to be negatively buoyant of about 20N/m. The length of the pipe sections were 3600m. The means and the spreads used at the time were extremely basic: two 1200 HP tugs for the tow operation, the radio positioning "Rana" to cover the operations, the tie-in ship Salvor equipped with lateral thrusters to provide a better control.

During several months of testing the team did not experience any loss or damage of the pipe or installation equipment. The proposed tow method (**Figure 3**) and pipeline assembly were validated successfully.

Surface tow trials in the North Sea (November-December 1975).

In 1975, the French associative research group Pipe Acier Profond conducted a full-scale test. The objectives were to prove the feasibility of such operations in rough sea states and to correlate full-scale test measurements with theoretical results. Two configurations were tested: surface tow and subsurface conditions.

The pipe used for the trials was a X65 16" OD with a wall thickness of 15.88mm. The string was 1000m long and was fitted with 50 buoyancy elements, 16 " diameter, 10 m long each: Half of the floats was attached along the pipe for the surface condition and released in a sling attach configuration for the suburface application. The pipe was fabricated in the area of Cromarty Firth (disused Evanton airport, near Invergordon-Inverness). The tow operation took place in the area of Moray Firth.

The surface tow test was conducted from the 23rd to the 29th of November 1975 in sea states reaching Hs=4m at a maximum speed of 6 knots. (**Figure 4**)

The subsurface tow test was conducted from the 1st of December to 6th of December 1975 in sea state reaching Hs=8m and wind of 60knots.

The pipe string was equipped with an instrumentation system for the measurement and record of 32 parameters including strain gauges for horizontal and vertical bending, load cells for towing force and forces on the floats, accelerometers. Wave was also measured and spectra were determined.

The collection and review of data concluded to the feasibility study both for surface and subsurface operations. The stress level was in the range of those calculated.

Deep Water Tow Operation for Girassol Project (2001)

The Girassol field development, offshore Angola in 1,400m of water, has stringent operating requirement due to flow assurance and flexibility requirements. The established solution was the selection of freestanding Hyperflow Riser Towers, insulated flowline bundles and mid-depth export system. These innovative concepts required substantial development, qualification and testing throughout the project. The installation was a critical part, and the lessons learnt are useful references for other deepwater development.

Towing of the Hyperflow Riser Towers:

The Hyperflow Riser Towers were towed on the sea surface 600km from the Lobito yard to the Girassol site. Once on location, they were upended, connected to the riser tower anchor.

Towing the structure in a buoyant state had been decided for safety reasons and to ensure the reversibility of the operation at any stage of the installation program. The towing spread involved the DP lead tug Seaway Explorer and the trail tug Seacore Voyager, with the American Pride as guard and assistance vessel during the towing operation.

An extensive testing program was performed before the towing to validate the towing engineering:

- Towing tests at tow tank facilities (**Figure 5**).
- Upending tests at military facilities in south of France.
- Full-scale tower tow test in Scotland to confirm that the external skin of the tower did not peel off.
- Trial surface tow test with Explorer and Seacor Voyager to validate vessel control procedure and train offshore personnel.

The trail towline consisted of a ballast chain, which controlled the depth of the Hyperflow Riser Tower buoyancy tank and act as a spring to a constant holdback tow tension. A safety surface buoy is also attached to the tower to prevent it from descending too deep in case of accidental flooding or loss of the ballast chain by the trail tug.

After the Hyperflow Riser Tower had left Lobito Bay, the buoyancy tank was submerged to a depth of –50m from surface by progressively deploying the ballast chain from the trail tug to reduce the stress generated by waves (**Figure 6**).

Two motion recording units (MRU) were installed on the first Hyperflow Riser Tower (one at the foot extremity and the other one 100m from the extremity) to collect motion data during the towing operation. American Pride, equipped with a Datawell buoy, recorded the seastate conditions so that the actual structure fatigue damage ratio could be estimated directly on site during the towing operation. Tension meters installed onboard recorded both trail and lead tensions. An acoustic transponder with a depth sensor monitored contiguously transmitted the depth of the buoyancy tank to the trail tug. The 600km-tow route was carefully engineered using fatigue simulator software developed specifically for that purpose.

The lead tug towed the structure using 80%-90% of its power at a tow speed, which varied from 3.5knots (kt) to 4.2kt and a maximum dynamic tension reaching 1700kN. The trail tug applied a constant back tension of 300kN.

The tow master and ship captains were monitoring the behavior of the Hyperflow Riser Tower and towing vessels using a tug management system and Differential Global Positioning System installed on board each ship. The convoy behaved extremely well during the whole towing operation and both captains did not experience any problems controlling their respective routes.

The three towing operations were carried out successfully without structures damage reported after inspection. The cumulative fatigue damage was well below the targeted limit.

Towing and fatigue analysis for the Hyperflow Riser Towers:

The towing and fatigue analysis is an area where close interface and cooperation between design and installation engineering is essential. A 3-D numerical model using Orcaflex software was first developed to evaluate the fatigue damage generating by environmental conditions.

A test tank program was carried out next on a scale model to verify and validate the numerical analysis. Both approaches confirmed the behavior of the tower in towing conditions.

Fatigue damage response amplification operators (Fatigue RAOs) were thus established. Weather statistics in Angola were analyzed to predict a typical scenario based on wave occurrence for yearly seastate conditions. The limiting seastate were identified in terms of wave incidence (**Figure 7** and **Figure 8**).

A software simulator was developed to be used to optimize the towing routes, provide a live structure fatigue damage ratio during the operation, and also confirm the weather window.

The as-built fatigue ratio was finally calculated by inputting the seastate and tow conditions into the simulator. After the tow, the data collected at MRU was analyzed. The comparison showed that the motion along the Hyperflow Riser Tower was similar and the fatigue damage induced was less based on MRU data that those predicted by simulator. (**Figure 9**).

Resonance phenomenon of a long string pipe towed on surface

Resonance phenomenon is resulting from the amplifiation of a periodic " quasi-static loading “, when the natural frequency of the structure is close of the loading period.

In the case of a pipe string, there is an infinite possibility for the natural modes of vibration .The natural mode number 'n' is defined by

The shape of the vibration Xn(x) :

$$Xn(x) = \sin(n.\pi\ .x/L\ ) = \sin(\pi\ .x/L_n)$$

With Ln equal to half of wave length: Ln=L /n

The natural period Tn

$$Tn = 2.L^2/(n^2/\pi)\sqrt{m/EI}\ =2.Ln^2/\pi\ \sqrt{m/EI}$$

In the above formula, m is the total unit mass including own mass of pipe and of floats cumulated with the hydrodynamic added mass. The value of m is typically 600 kg/m for a 16 " pipe and 5000 kg/m for a tower. EI is the bending stiffness, in the range of 90000 kN.m2 for a 16 " pipe and 500 000 kN.m2 for a tower. In the case of a 1000m string the first natural period is in the range of half an hour for both cases, which is obviously well above potential wave periods. The natural modes with a frequency in the range of wave frequencies are between the tenth and the twentieth modes.

The resonance may be an issue only if the quasi-static loading is not too small. Such cases occur when the wave length Lw. is equal to wave length of the mode n with same frequency, in the case where wave direction is in line with pipe string The resonance period Tr is equal to both natural period and wave period with following conditions.

$$Lw = 2Ln$$

$$Lw = gTr^2/(2.\pi)$$

$$Ln^2 = \pi.Tr/2\ .\sqrt{EI/m}$$

The condition 2.Ln = Lw is obtained if

$$Tr = 2.\pi.\sqrt[6]{EI/(m.g^4)}$$

With here above cases the resonance critical period Tr is between 9 and 10 s.

In the case where there is an angle θ between pipe direction and pipe string (**Figure 10**), the condition Lw = 2.Ln has to be modified in

$$Lw = 2.Ln.\cos(\theta)$$

The impact of the angle on the critical resonance period is

$$Tr = 2.\pi\ .\sqrt[6]{EI.\cos^4(\theta)/(m.g^4)}$$

Main parameter for the amplification factor between the quasi-static and dynamic responses is the damping. The evaluation of the hydrodynamic part of this damping remains a major issue.

A New Surface Tow Technique – Surface Wave Tow Configuration

Based on operation experiences and considerations presented above, Acergy has developed a new tow configuration – Surface Wave Tow configuration (patent pending). This approach is to keep the pipe surface or sub-surface most of the time, but can cope with a variety of water depths as well (**Figure 11**): e.g. off-bottom tow in very shallow water.

The surface wave tow eliminates the need for applying a permanent tension during the tow and thus allows laying the pipe along a curved route. Numerical simulations have shown that a pipe length of up to 10km could be towed either on surface or subsurface with only a lead and trail tugs. Pipes of 20km could also be towed in a similar manner with the assistance 3 additional guard vessels. Regarding pipe fatigue damage and marine traffic risk during surface tow, the Girassol experience has demonstrated that the numerical models can predict pipe behavior relatively accurately (except for resonance phenomenon) and the marine activities can be monitored by the guard vessels assistance.

Tow Arrangement Design

The pipe is made globally positively buoyant, thus the bollard pull requirement is reduced. The buoyancy modules are distributed along the pipeline as positively and negatively buoyant sections to give an undulated wave shape configuration. This makes the buoyancy adjustment operation much easier compared to those in a control depth tow. A lead tug provides the bollard pull required for the tow, a trail tug maintains the back tension required for controlling the curvature of the pipeline, guard vessels adjust the pipe elevation by means of a ballast chain attached (**Figure 12**). Adjusting both extremities and intermediate elevations also allows the controlling the pipe curvature and for shorter pipelines this can be done without the assistance of the guard vessels. Guard vessel can be disconnected from the pipe and intervene rapidly on both side of the pipe. A tug radio management system assists the tow master in co-ordinating the convoy. In case of lateral current the tow heading has to be adjusted and aligned with the vector combining towing speed and lateral current as shown in **Figure 13**.

During laying one pipe extremity is deployed within a target area using a deadman anchor and the pipe is laid with an S shape the buoyancy installed along the pipe is acting as a stinger to support the line. Tugs are positioned to orientate the line and take into consideration the subsea current profiles.

Physics of A Pipeline Towing System

As all tow systems, Surface Wave Tow configuration consists of a pipeline, chains, towline wires, and tow vessels (lead tug, trail tug etc). The success of the tow operation depends on the careful and accurate consideration of the behavior of each component and its interaction with between each other under environmental conditions.

When the towed pipeline gets very long (>5m), the risk of damage increases because they are directly exposed to environmental loading. The physics of a towed pipeline in currents and waves is extremely complex. Statically there exists a significant structural nonlinearity, dynamically a combination of quadratic nonlinear hydrodynamic drag force and an usual near-tangential inertial force. Moreover, these are further complicated by the horizontal/axial dynamic interaction of the pipeline, tow wires and tow vessels, especially when the towed pipeline is long, and tow wire is flexible, the mass of the towing vessels is comparable with that of the pipeline.

For a traditionally long pipeline tow systems, the responses of the pipeline is very sensitive to the longitudinal, or surge, component of excitation due to its geometric characteristics. In order to soften these phenomena, flexible tow wire could be used. For the Surface Wave Tow system, the wave shapes built in the configuration play a very favorable role in the axial dynamics by absorbing some portion of the dynamic force excitation from the tow vessels.

Although a towed pipeline experiences large deformation compared to its diameter, this deformation can be assumed to be small compared to its global dimensions such as pipe length or maximum sagging. Under this small deflection assumption, the governing equations for a slender beam element (**Figure 14** and **Figure 15**) is:

$$
\begin{aligned}
&EI_z y^{(4)} - Ty'' = f_y(x) \\
&(m+m_a)\ddot{y} + c\dot{y} + EI_z y^{(4)} - Ty'' = f_y(x,t)
\end{aligned} \qquad (1)
$$

where:
EI : bending stiffness
T : line tension
m : mass per unit length
$m_a = \frac{1}{4}\rho\pi D^2$
c : a damping coefficient of the pipe
$f_y(x)$: a static force
$f_y(x,t)$: a dynamic force

The static force $f_y(x)$ consists of pipe self weight, drag forces, hydrostatic pressure force on the pipeline. The dynamic force $f_y(x,t)$ is made of drag and inertia forces on the pipe. The hydrostatic pressure forces on curved pipe can be calculated by:

$$
\begin{aligned}
dF_x &= \left[\left(P_i A_i - P_o A_o\right) + r\left(r_i A_i - r_o A_o\right)\left(\cos\theta - \sin\theta d\theta\right)\right] \cdot \sin\theta d\theta \\
dF_y &= \left[\left(P_i A_i - P_o A_o\right) + r\left(r_i A_i - r_o A_o\right)\left(\cos\theta - \sin\theta d\theta\right)\right] \cdot \cos\theta d\theta
\end{aligned} \qquad (2)
$$

where:
θ : angle from x-axis to the axis of a pipe element
P_i : internal hydrostatic pressure
P_o : external hydrostatic pressure
A_i : pipe internal cross section area
A_o : pipe external cross section area
r_i : specific weight of pipe internal fluid
r_o : specific weight of pipe external fluid
r : specific weight of fluid

The extended form of Morison's equation can be used to calculated the hydrodynamic drag and inertia forces:

$$
F_w = \left(D \cdot a_w + C_a \cdot D \cdot a_r\right) + \frac{1}{2}\rho v_r |v_r| C_d A \qquad (3)
$$

where:
F_w : wave force
D : mass of fluid displaced by the body
a_w : fluid acceleration relative to earth
C_a : added mass coefficient for the body
a_r : fluid acceleration relative to the body
r : density of water
v_r : fluid velocity relative to the body
C_d : drag coefficient for the body

A : drag area

Offshore engineers usually consider only the component of the current normal to the pipeline for the calculation of drag forces. This is quite reasonable for most common offshore structures such as risers since the forces due to a tangential component are negligible compared to those due to a normal one. In the case of towed pipelines, however, circumstances are totally different. When the towed pipe is long and experience high tow speeds with a small angle of attack, the total frictional drag force due to tangential component of a current is quite large and it directly influences the structural behavior of the pipeline in the forms of tow tension. Also it contributes to the maximum tow wire tension, which is critical in selecting the tow vessels with proper bollard pull capabilities.

From the governing equations of the pipelines and the mechanical property of the towlines, three principal nonlinearities can be identified:

1. The deformation (curvature) – dependent tension of pipelines.
2. The nonlinear drag force on pipelines, proportional to the square of the relative velocity between a pipeline and fluid.
3. The nonlinear tension-axial deformation of towlines.

Numerical Assessment of Surface Wave Tow Configuration

Although an analytical solution of the governing equilibrium equations of the pipeline is possible if many simplifications are made, as a result of these simplifications, the solution lacks accuracy and practical applicability. Therefore a numerical technique must be utilised, which is the most powerful and accurate technique for non-linear analysis. It allows calculation of non-linear drag forces due to relative pipe and fluid motions and modification of the stiffness matrix according to instantaneous system response on the basis of geometric non-linearity.

In order to investigate the feasibility of the Surface Wave Tow configuration, numerical analysis using Orcaflex software was performed to ensure the pipelines have acceptable levels of deformations and stress due to forces induced by currents, waves and surface vessel motion during the tow operation. The Surface Wave Tow system was also examined for the sensitivity and limits of applications in terms of key parameters.

Surface Wave System Computation Model

Four types of pipeline (20km) were studied for typical tow operations using Surface Wave Tow configuration. The pipe data and the net buoyancy required are presented in **Table 1**. The pipelines are design for 1800m-2500m water depth with OD of 14”-24”. Buoyancy modules were distributed along the 20km of pipe to provide 3 positively buoyant sections of about -55N/m and 4 negatively buoyant sections of about 55N/m. The buoyancy is assumed to be syntactic foam made of microspheres, macrospheres and epoxy matrix. The specific gravity of the foam is taken as 460kg/m3, based on a deep-water project in West Africa. A preliminary float design is presented in **Figure 16**. The guideline of designing the float was considered as:

- Minimal extra drag force introduced by float on the pipeline
- Deep water pressure resistance for recovery and reuse
- ROV friendly
- Maximum float group spacing allowed by pipe stress level for maximum offshore installation/release rate
- Clamp attachment without welding requirement on the pipeline.

Tow convoy was included in the model and vessel motion was simulated by RAO data of the lead/trail tugs and guard vessels respectively. The tow wires were assumed to be a 6x19 rope with 3” wire core.

Numerical Simulation Results

Dynamic simulations were performed to check the pipeline responses under hydrodynamic loading due to wave/current, towing vessel motion etc. Main results from analysis and operational parameters for a typical tow operation are presented in **Table 2**. **Figure 17** and **Figure 18** demonstrate the 20” OD (1.025”WT) pipeline configuration profile (vertical and lateral) during the towing operation under different heading angles. Note that the scales in the figures are different: the pipeline length in 5000m, while the vertical and lateral in 50m. **Figure 19** through **Figure 21** give the tension, stress and bending moment distribution alone the pipeline during the towing.

The bollard pull requirement for the towing operation was found to be proportional to the pipe submerged weight. Pipes #3 (20”) and #4 (14”) had similar submerged weights, so were the maximum pipe tension levels during the tow. Pipe #2 (20” 1.025”WT) had the heaviest submerged weight (1019N/m), which led to highest tow tension (>200te).

When the pipeline was subject to lateral current, it would move near to the horizontal plane and also depart from its straight path. The beam sea condition would generate the largest lateral displacement, stress and tension level in the pipe **(Table 2**, **Figure 18**).

When the pipe is under mean static condition (no current), the pipe vertical profile is uniformly distributed along the 20km, with the maximum vertical displacement in the middle sags. When the towing started and the pipe was moving forward, large vertical displacement would always accumulated towards the end (last sag) of the pipeline. The head sea generated largest displacement (**Figure 17**).

While the pipe sections close to the lead tug experienced highest tension and von Mises stress level, the section close to the trail tug had largest bending moment (also bending stress).

A typical deep-water normal lay operation was also checked for the surface Wave tow configuration. The results are presented in **Figure 22** through **Figure 27**.

Sensitivity Study

The impact of the pipeline length was investigated. For pipeline #2 (20”OD 1.025”WT), 3 optional towing lengths (5km, 10km, 15km) were modeled and results compared with those of the 20km tow. Static configurations for the shorter tows were set up first by adjusting the distance between the lead tug and trail tug to achieve the same static pipeline tension (51te) as the base case 20km long tow under mean static condition. Then identical dynamic loading (head sea – load case 2) was applied and simulated. As expected, the maximum pipeline tension, stress **(Figure 28**) and vertical displacement (**Figure 29**) could be reduced significantly if the pipeline length to be towed was shortened. A greater than 200te bollard pull requirement for a 20km tow would turn to a 100te tow for the 5km pipe and under same loading condition. The former condition indicated a two-lead tug operation with higher risk, while the latter a one-lead tug tow with lower risks.

For the 5km tow system, the impact of the tow speed was also checked for pipe #4 (14"OD 0.75"WT). In addition to the mean static condition (0 knot current), head sea conditions with currents of 2.5knots to 6.5knots with 1knot increment were applied and the results are given in **Figure 30** through **Figure 32**. Assuming a 200te bollard pull capacity for tow tug, the limiting speed for the combined surface current is about 5.5knots, which is corresponding to 4 knot towing speed if the surface current is 1.5knots head sea. The associated maximum dynamic tow tension was 170te. It is also shown that the higher the towing speed, the deeper the last sag of the pipe: 37m in water depth for a 5.5knots towing (combined current speed).

To investigate the influence of the tow wire stiffness, dynamic simulations were performed with different axial stiffness of the tow wire, EA/100, EA/10, EA, EA*10, and EA*50 are compared (**Figure 33**). The impact on the pipe responses due to stiffer tow wires (EA*10, EA*50) is found to be negligible. However when the tow wire is very soft (EA/100), the tension would decrease by 19% (**Figure 35**), and the pipe vertical displacement near the trail tug end will increase significantly (-283m to -486m) (**Figure 34**).

Commercial Viability

The cost comparison aspect must take into consideration several aspect prior to conclude on the commercial viability of a tow solution) /6/. **Table 3** provides some elements to take into consideration when evaluating the overall performance of a surface tow operation.

Conclusions

Towing and laying along curved route long infield lines for deep-water field development is technically feasible. This type of operation was engineered and validated at the start of the offshore industry in 1960 and the results found is still valid although progress made in software analytical tool allows to extend the method to longer pipeline by changing the way the buoyancy is distributed along the line. The tow method can be economically attractive if both the cost of the buoyancy and the cost of extra connection to make up the entire length are comparable with the cost of mobilisation of large laying ship.

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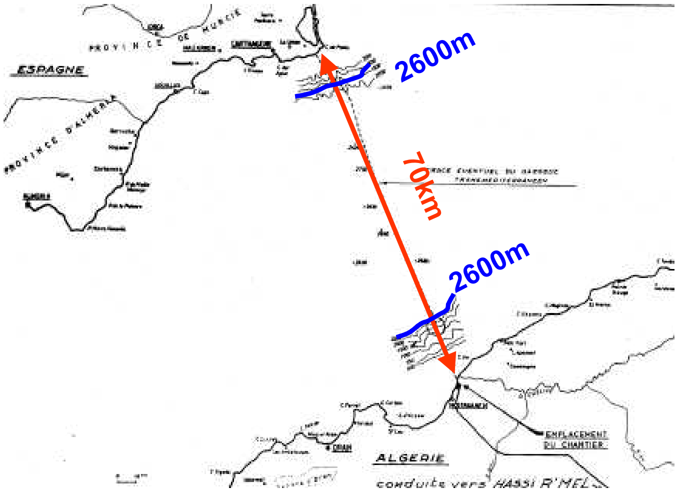

Figure 1 Route and Subsea Survey

Figure 2 Pipeline Surface Tie-in Operation

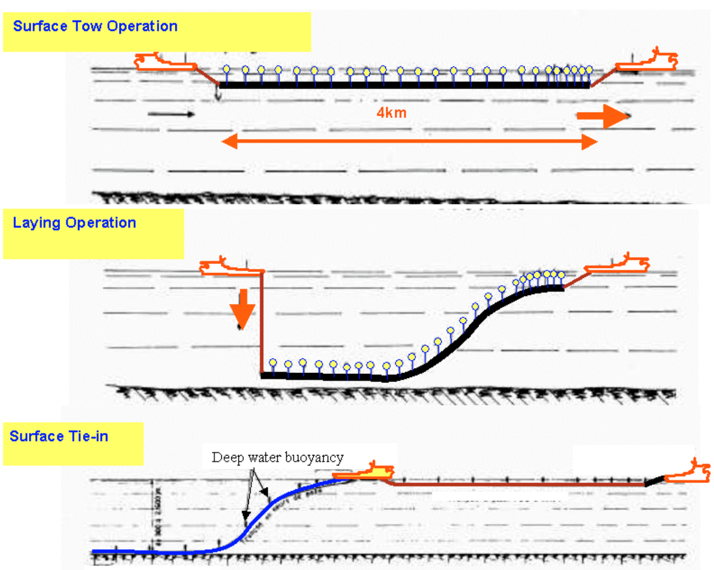

Figure 3 Towing and Laying Method for Mostaganem-Cartagena Pipeline Project

Figure 4 Surface tow trial North Sea November 1975

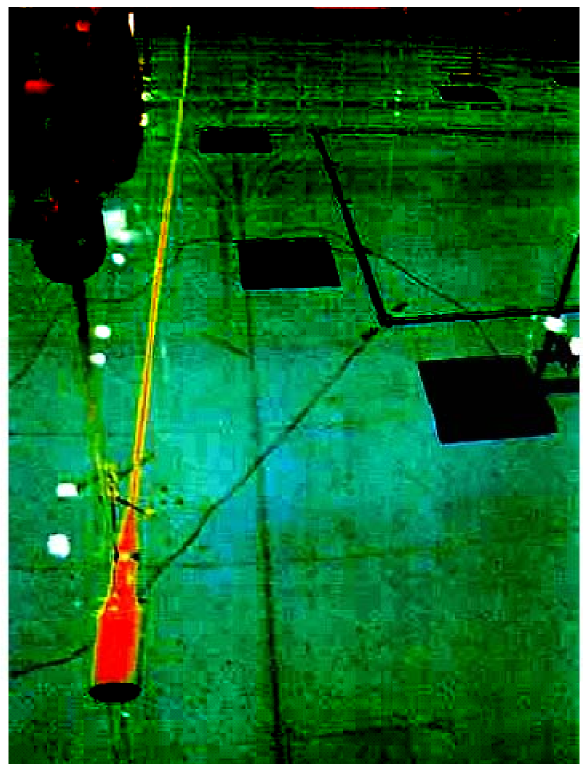

Figure 5 Hyperflow Riser Tower Model Test at Tow Tank

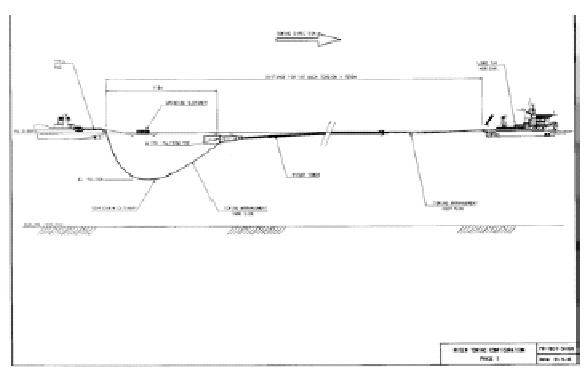

Figure 6 Girassol Hyperflow Rise Tower Towing Config in Lobito Bay

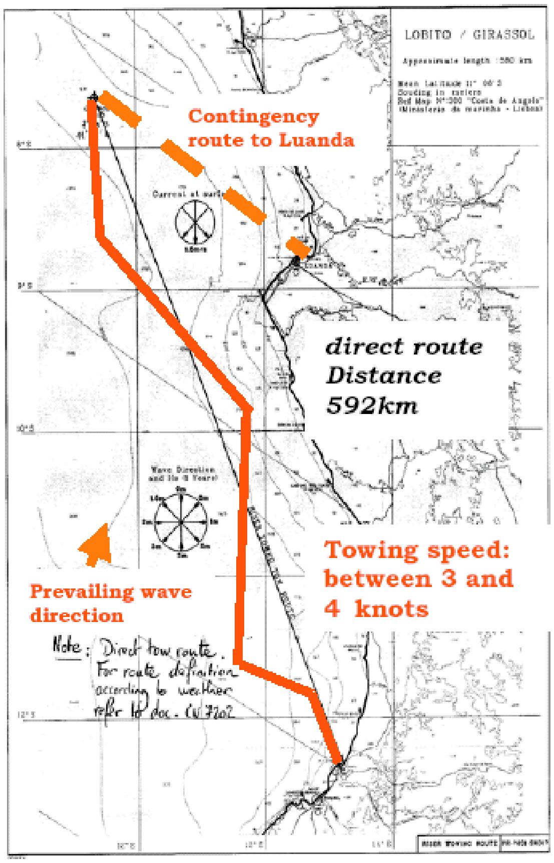

Figure 7 Hyperflow Riser Tower Towing Route to Girassol Field

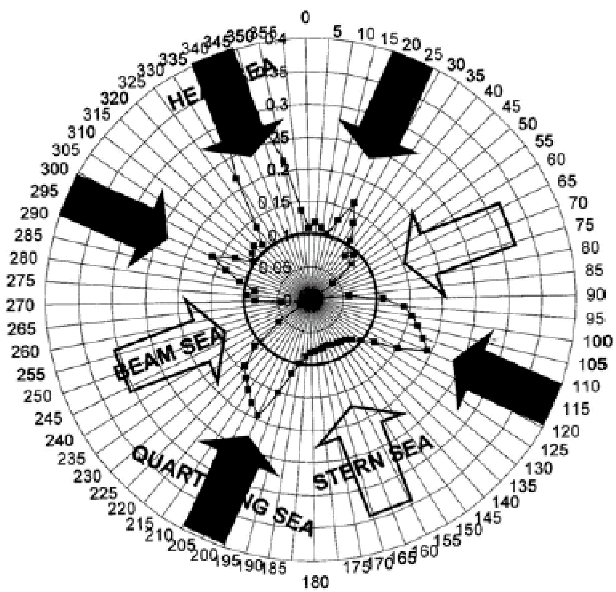

Figure 8 Fatigue Diagram of Hyperflow Riser Tower during Tow

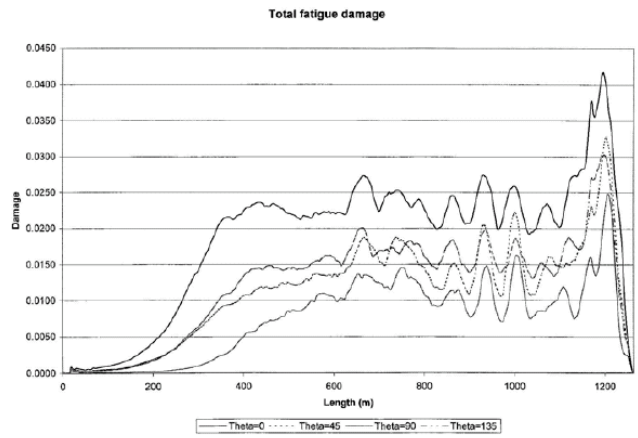

Figure 9 Fatigue Diagram Ratio along the Tower

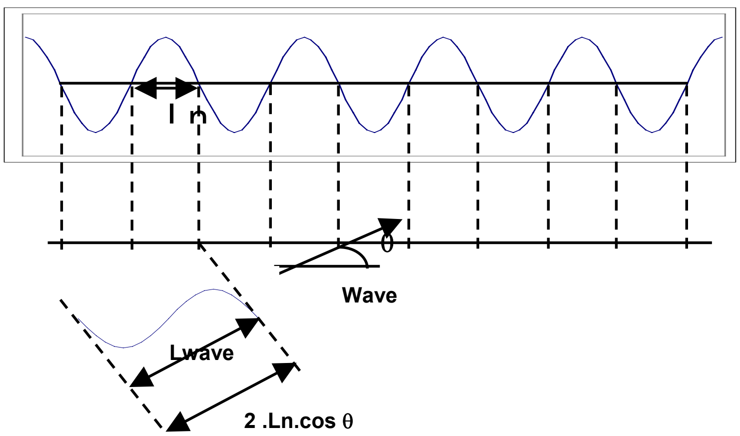

Figure 10 Wave length incidence matching self period of the structure

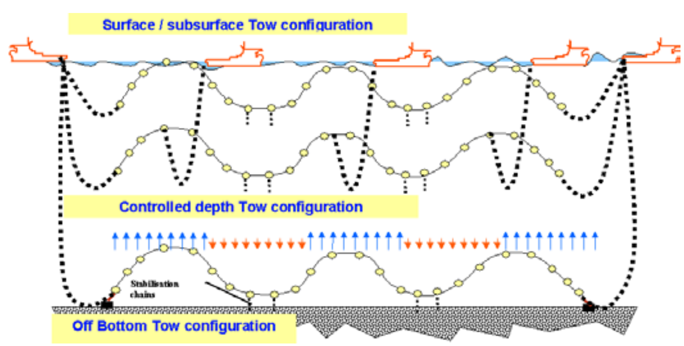

Figure 11 Wave Tow Methods

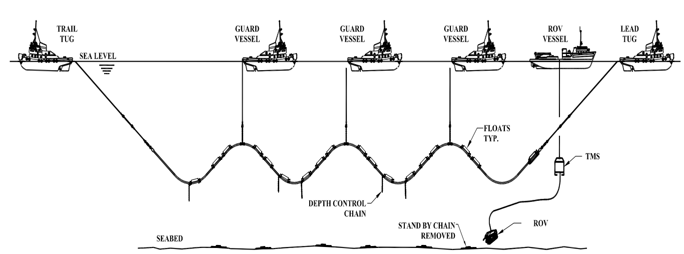

Figure 12 Surface Wave Tow Installation Arrangement

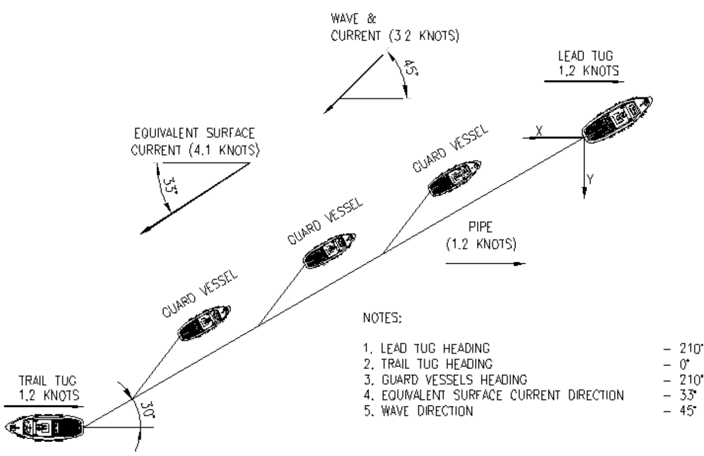

Figure 13 Tow Arrangement for Beam Current Condition

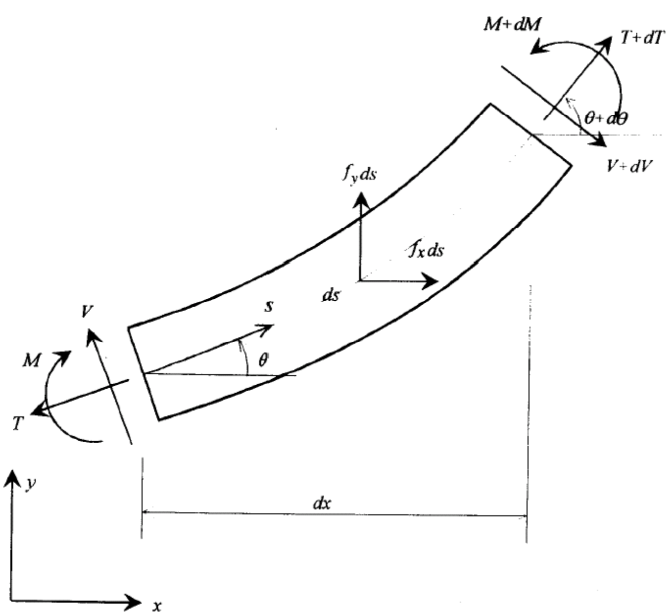

Figure 14 Free Body Diagram of a Slender Beam Element

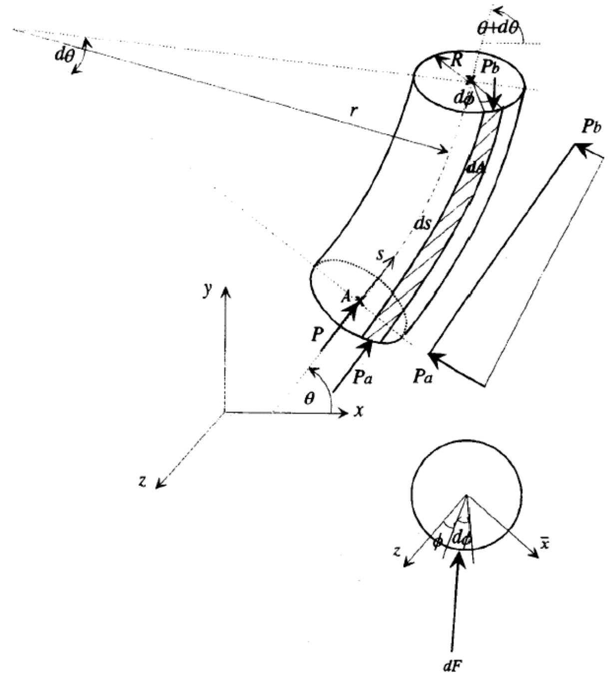

Figure 15 Hydrostatic Pressure Force on Curved Pipe

Table 1 Pipeline Data

Parameters	Unit	Pipe Type #1	#2	#3	#4
Outside diameter	mm	610	508	508	356
(OD)	in	**24**	**20**	**20**	**14**
Wall thickness	mm	26	26	22	19
(WT)	in	1.025	1.025	0.875	0.75
Pipe design water depth[1]	m	1800	2500	1800	2500
Steel Grade density X65	kg/m3	7850			
Mass in air	kg/m	375	310	266	158
Sea water density	kg/m3	1025			
Submerged weight	N/m	755	1019	585	563
Net buoyancy requirement	Te	1540	2025	1160	1114
Total Pipe Length	km	20			

Note: Assuming no buckle arrestors are included along the pipeline.

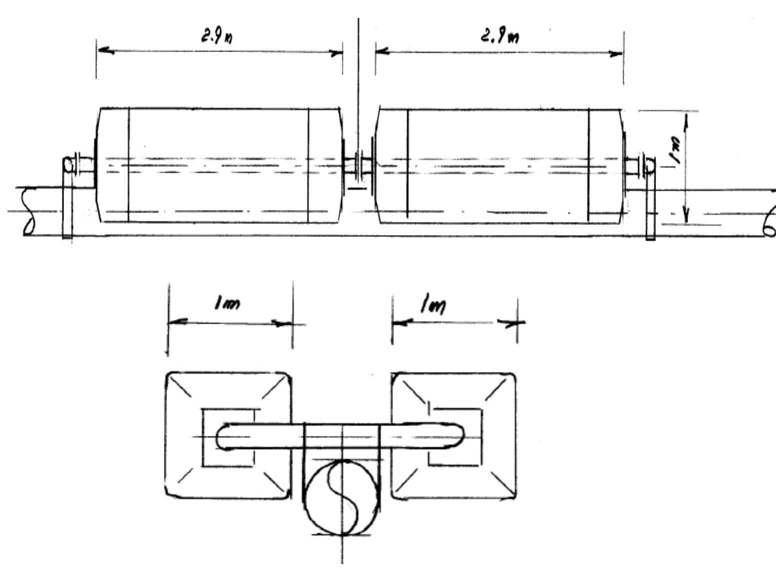

Figure 16 Preliminary Float Design

Table 2 Result Summary

Load Case	Condition		Max Pipe Loads		Pipe Profile	
	Wave/ Current Direction	Combined Surface Current Speed	Effective Tension	von Mises Stress	Max Water Depth	Max Lateral Displ.
	(from)	(knots)	(kN)	(Mpa)	(m)	(m)
24"OD 1.025"WT						
Case1	Head	0	508	25	-172	0
Case2	Head	3.5	1721	49	-247	0
Case3	Beam	3.5	1969	59	-189	215
Case4	Beam	3.2	1653	57	-190	329
20"OD 1.025"WT						
Case1	Head	0	549	25	-181	0
Case2	Head	3.5	2113	59	-263	0
Case3	Beam	3.5	2453	72	-195	95
Case4	Beam	3.2	2006	62	-207	191
20"OD 0.875"WT						
Case1	Head	0	534	24	-177	0
Case2	Head	3.5	1369	38	-234	0
Case3	Beam	3.5	1563	43	-191	69
Case4	Beam	3.2	1308	44	-197	118
14"OD 0.75"WT						
Case1	Head	0	544	34	-183	0
Case2	Head	3.5	1330	69	-238	0
Case3	Beam	3.5	1509	80	-198	38
Case4	Beam	3.2	1280	72	-197	24

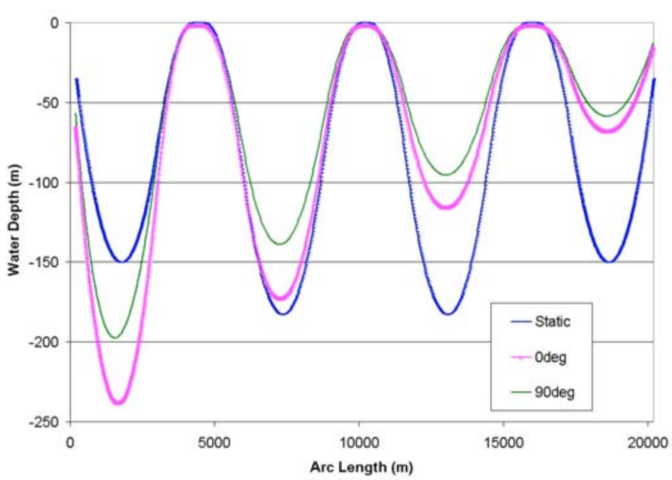

Figure 17 Vertical Profile – During Tow under Current

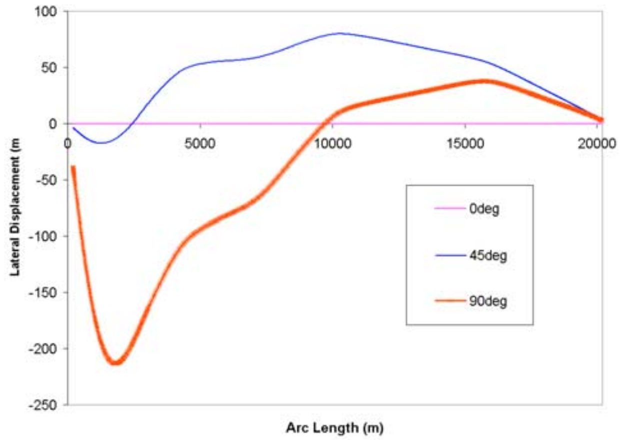

Figure 18 Pipeline Lateral Displacement

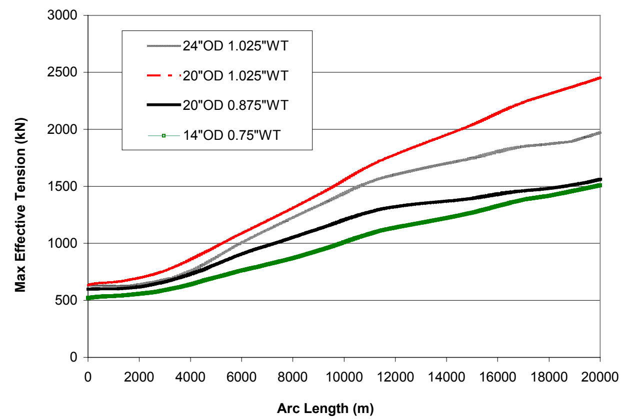

Figure 19 Tension Distribution

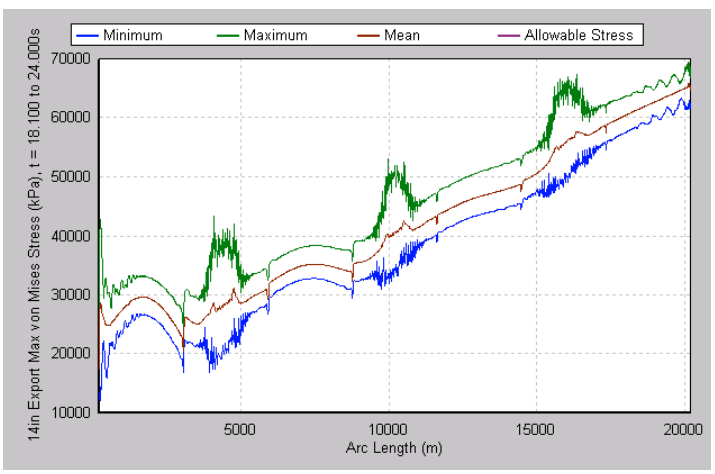

Figure 20 Stress Distribution

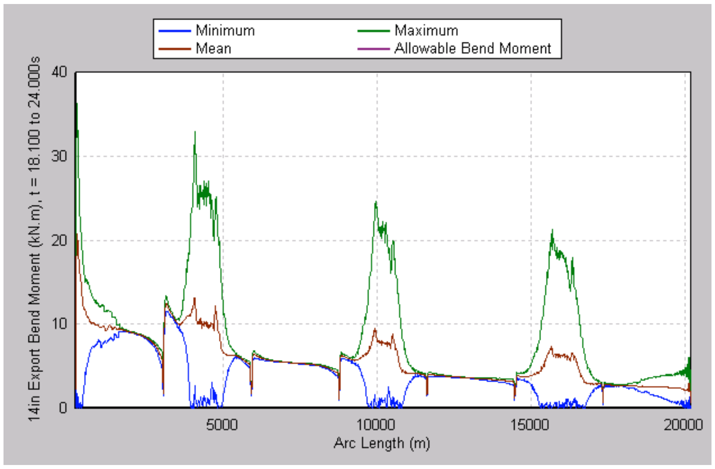

Figure 21 Bending Moment Distribution

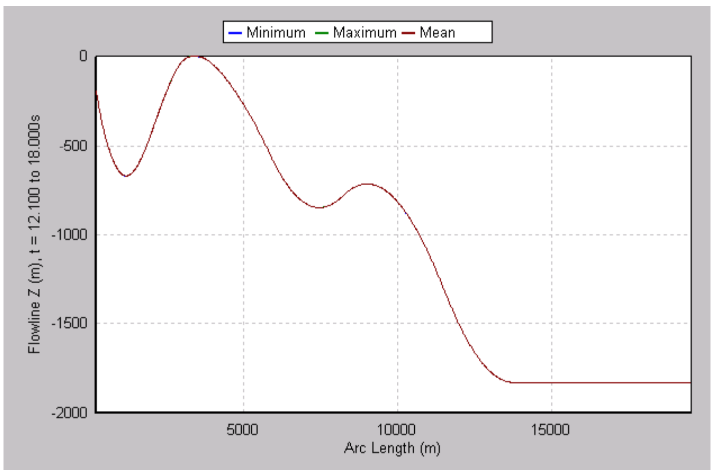

Figure 22 Pipe Lay Vertical Profile – Head Sea

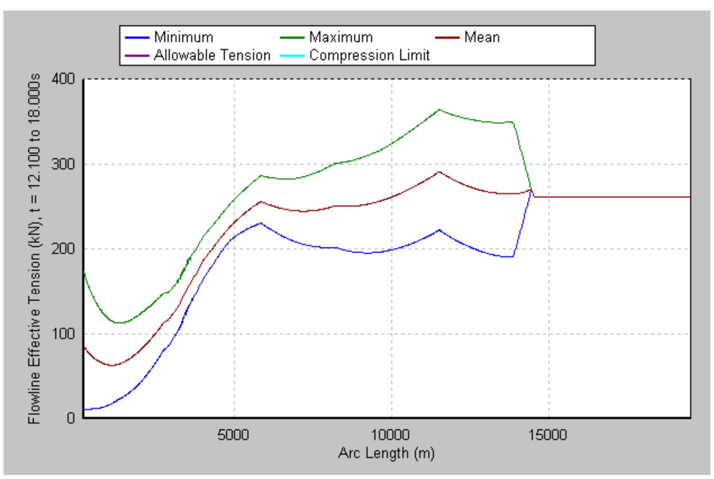

Figure 23 Tension Distribution during Laying – Head Sea

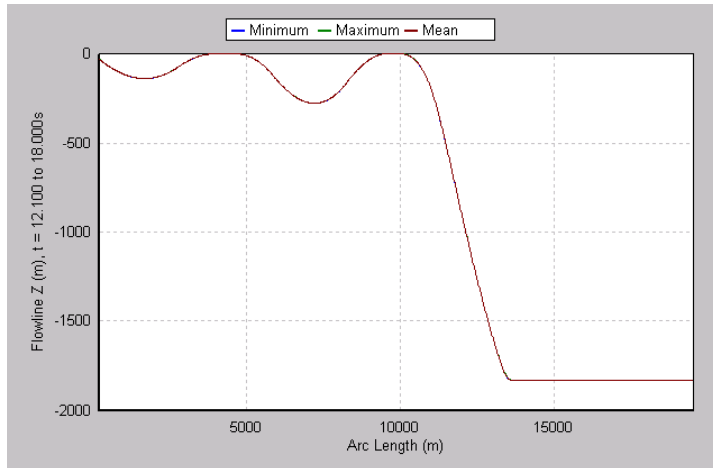

Figure 24 Pipe Lay Vertical Profile – Beam Sea

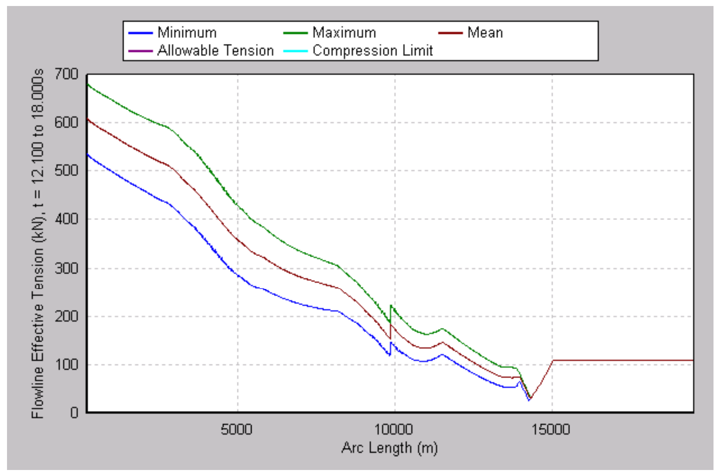

Figure 25 Tension Distribution during Laying – Beam Sea

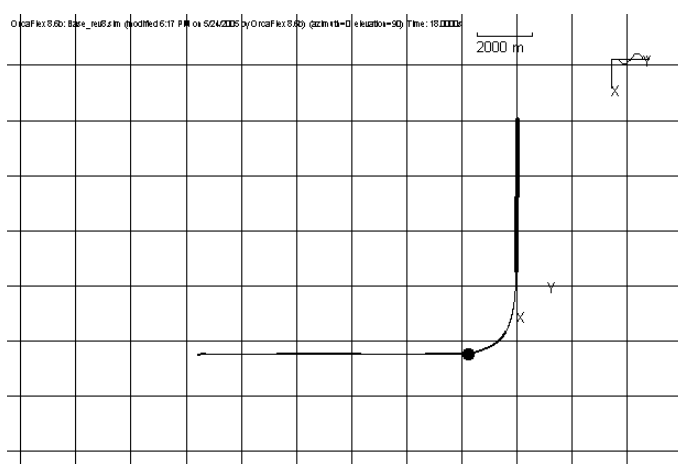

Figure 26 Pipe Lay Operation

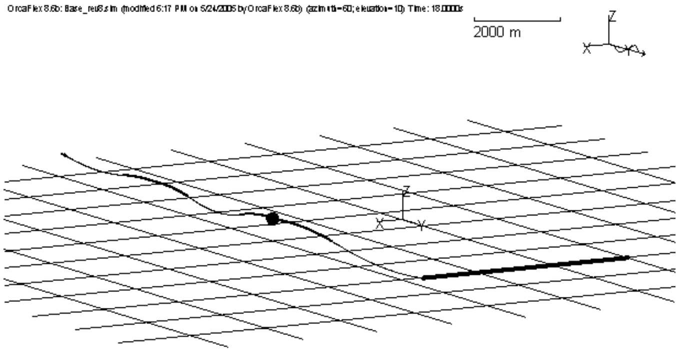

Figure 27 Pipe Lay Operation

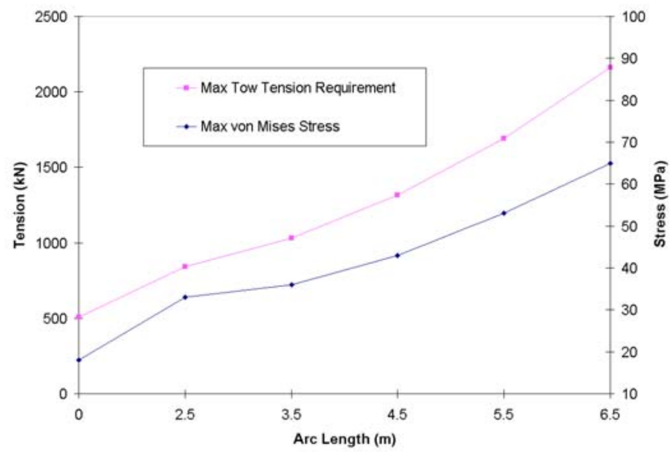

Figure 30 Velocity Sensitivity (Max. Tension/Stress)

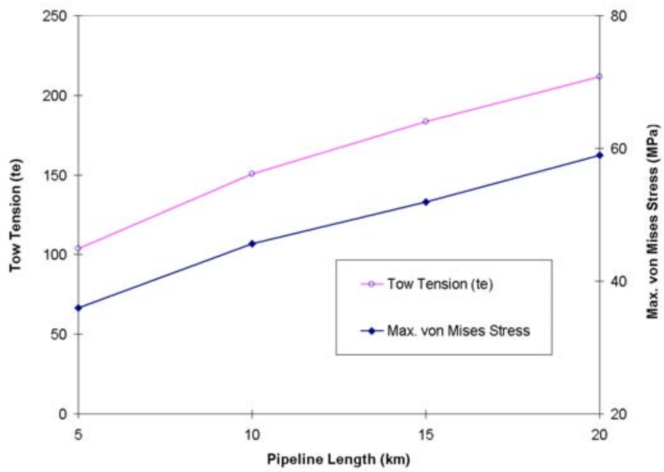

Figure 28 Pipeline Length Sensitivity (Tension/Stress)

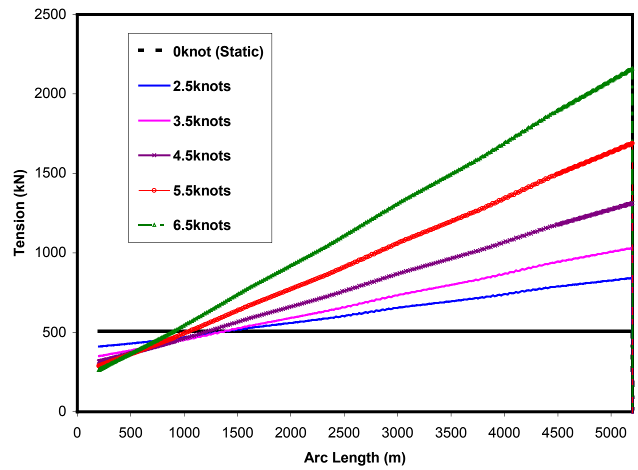

Figure 31 Velocity Sensitivity (Tension Distribution)

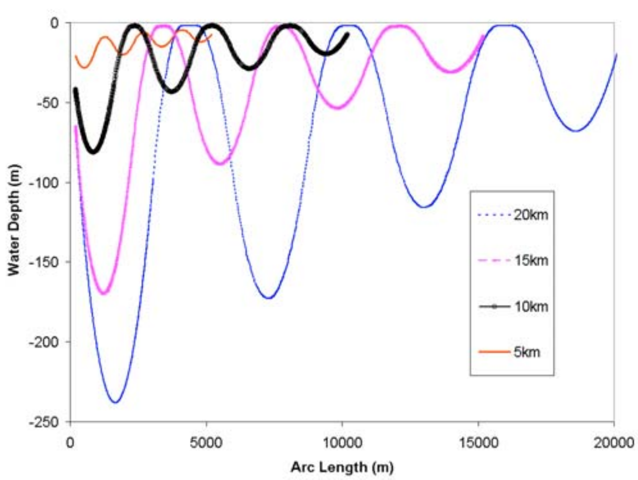

Figure 29 Pipeline Length Sensitivity (Vertical Profile)

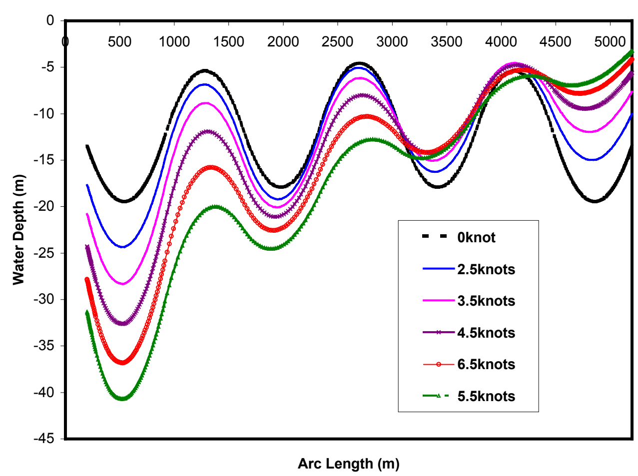

Figure 32Velocity Sensitivity (Vertical Profile

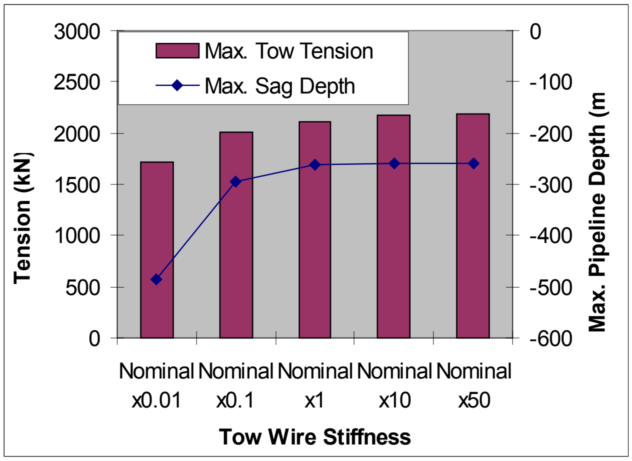

Figure 33 Tow Wire Stiffness Sensitivity

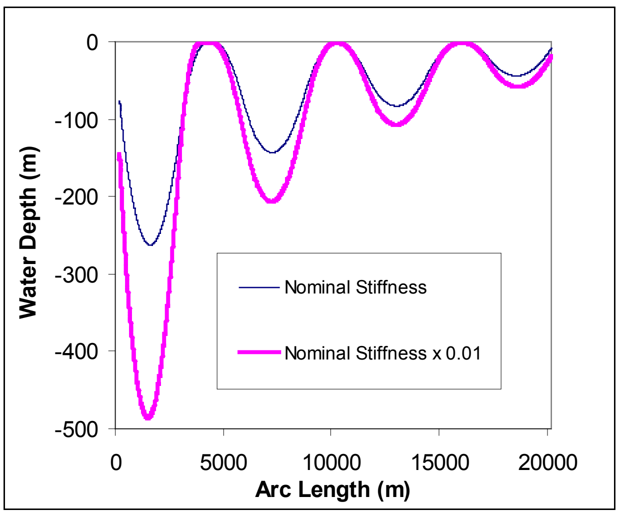

Figure 34 Pipe Elevation – Stiffness Sensitivity

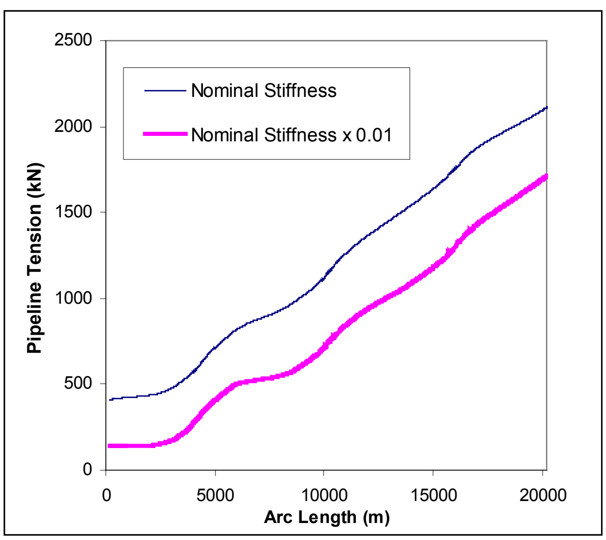

Figure 35 Tension Distribution – Stiffness Sensitivity

Table 3 Commercial Impact Comparison

Cost Element	Tow	Reel Lay
Buoyancy	$4000-$5000 per metric ton	Marginal cost.
Cost of a Deep Water Laying Spread	Depends on the market typically 4 x tugs at an average of $25,000 a day	Depends on the market typically $150,000-$250,000 a day.
Installation Timing	Typically pipe can be towed at speed of 3-4 knots, 2 additional days are required for positioning and laying on site. Depends on tow distance.	Depend on the loading capacity, transit speed of the ship and distance between fabrication yard and offshore site. Laying speed once on site can be 400m/hrs plus additional days for initiation and abandonment.
Mobilisation & Demobilisation	Typically 2-3 days for local tugs.	Depends on the transit distance and speed.
Pipeline sleds	Sleds are towed with no additional installation time and minimum fabrication cost (additional buoyancy).	Installation of the sled is time consuming and often requires some buoyancy.
Number of lines.	Bundled lines allow optimisation of the installation scope.	Basically each line needs to be installed separately.
Intermediate connection.	Cost of sleds, connectors and spool in case a subsea intermediate connection.	Pipe may have to be abandoned and recovered later.
Mitigation measures for lateral buckling and pipe walking.	Production pipes encapsulated inside a carrier pipe are not subject to lateral buckling or pipe walking.	Cost for providing anchoring and slippers to accommodate lateral buckling and pipe walking requirements