◉ 技術報告

Advanced Offshore Pipelaying Analysis Techniques Part 2 : Laybarge Methods

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(95년 8월 30일 접수)

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Key Words : Laybarge Method(가설선 법), Pipe Stress Analysis(파이프 응력 해석), Offshore Pipeline Installation(해저 파이프라인 가설)

Abstract

Various laybarge methods for offshore pipeline installation are introduced. Pipe stresses and strains during the installation are discussed with linear and nonlinear analysis methods. Several operational modes of offshore pipeline installation are described. Computer modelling techniques of the pipeline installation analyses are suggested.

1. INTRODUCTION

As more offshore pipelines are installed in increasingly deep water, many specialized design and installation problems have to be solved to meet the new challenges. Today, deep water generally means more than 300 m and very deep water means 1000m or deeper for offshore pipeline installation. To date, there have been at least 31 pipelines in the Gulf of Mexico in water depth greater than 300m. Other areas with deep water pipelines (excluding flexible lines) are : 4 lines in U.S west coast, 3 lines in Brazil, 5 lines in the North Sea, 3 lines in South East Asia, and 3 lines in the Middle East.. Currently, there are at least 34 deep water pipeline projects worldwide in progress or pending (start-up in 1995 or 1996). Of therse, 18 lines are in the Gulf of Mexico.[1] These deep water pipelines must be designed such that they maintain structural integrity during the installation and operational lifetime.

It is apparent that very deep water pipeline installations receive unprecedented attention.[2)3)4)] Some of the examples are as follows ; Recently two 660 mm diameter pipelines were installed

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across the Mediterranean Sea in the depth of 600m.[5)6)] These pipes were laid on very rough seabed under storng current. In the Gulf of Mexico, two 324 mm pipelines were laid in water depth of 874 m with a J-lay system developed by McDermott International.[7)8)] These pipelines were connected to Shell's Auger tension leg platform (TLP). The Augur TLP set a world water depth record for a drilling and production platform. Shell plans to install a second TLP and pipelines in 894 m of water in 1996. Another two 610 mm internal diameter gas pipelines with a distance of 1140 km are planned to be installed from Oman to India across the Arabian Sea.[9)] The maximum water depth is 3525 m and this depth is three times greater than existing offshore pipelines. These pipelines receive the greatest attention in this decade. The first of the two pipelines is due for completion in 1999. Offshore Technology Conference (OTC) 1995 will hold a special technical session for the Oman- India pipeline project which includes route survey, system design and formation of a technology development team, prototype line-pipe collapse test, welding NDT, corrosion, ROV capability, and in-service repair.

The objective of this technical report is to introduce the advanced analysis techniques of deep water pipeline installation using laybarge methods. Various laybarge methods are shown in Fig. 1 and the advantages and disadvantages of the various methods are shown in Table 1. Stress analysis methods using linear and nonlinear analysis techniques are discussed. Computer modelling techniques of the pipelay to improve the installation analysis with OFFPIPE[10)] are suggested. OFFPIPE is a nonlinear 3-dimensional FEM based program for the design and installation of offshore pipelines.

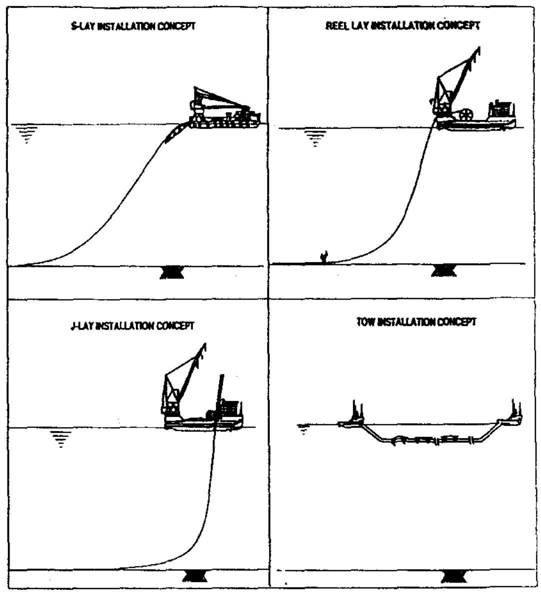


Fig. 1 SKETCHES OF LAYBARGE METHODS

2. LAYBARGE METHODS

2.1 S-Lay Method

This menhod consisting of a laybarge and a stinger and is the most common for offshore pipeline installation. The required equipment and their characteristics are shown in the previous report..[11)] Pipes are welded at the weld stations in the horizontal deck and sent to the seabed through the ramp and stinger. Pipes pass tensioners, weld stations, X-ray station, field joint and coating stations. The S-lay barges should be long enough to accommodate a reasonable number of working stations on deck and must have sufficient pipe loading capacity and space on deck for necessary laying equipment. The laybarge must have a proper combination of tensioning capacity and stinger. Conventional S-lay barges maintain positioning and station keeping by spread mooring lines and require additional vessels to handle the anchors.

Table 1. The Advantages and Disadvantages of Laybarge Methods

	ADVANTAGES	DISADVANTAGES
S-Lay Method	Horizontal ramp for welding stations	Vulnerable long stinger
	Most available laybarge	Dynamic pipe stress is high
	Proven method & equipment	High tension requirement
	Experienced technique	Limited turn radius on seabed
		Touchdown distance is long
J-Lay Method	Low tension is required	Less experience
	Good for very deep water	Slow lay rate
	Dynamic pipe stress is low	Limited barge availability
	Stinger is eliminated	Vertical single welding station
	Stress control is easy	Vulnerable to delay or breakdown
	Multiple joints can be laid	Pipe joints weld at onshore
	Small pipe installation crew	Crowded single work station
	Less welding repair	Not good in shallow water
	Thrust is independent of water depth	
Reel Barge Method	Fast lay speed	Limited pipe size
	Good for very deep water	Heavy wall thickness is required
	Assemble pipe at onshore	Dynamic positioning is required
	Large departure angle	Limited length by reel capacity
	High permissible strain	Limited barge availability
		Anode installation on barge
Tow Method	Fast lay speed	Limited pipe size and length
	Good for very deep water	Heavy wall thickness is required
	Quality control at onshore	Tow test and byoys are required
	Assemble pipe at onshore	Large make-up site is required
	Small vessels are required	

The barges move forward by taking the mooring cables on the bow and paying out cables on the stern as the pipe joints are laid out.

S-lay method used to be considered with a depth limitation of 300m, but various research and developments have been performed to extend this method up to 1000 m water depth by modification of the conventional laybarges.[12)13)] Another direct means of extending the depth capability of S-lay barge is to design the lightest pipe weight possible which still meets the requirements for bottom stability and collapse resistance due to combined bending and external pressure. There is a limited number of fourth generation laybarges capable of mooring with dynamic positioning system and lay large pipelines with high speed in water depth exceeding 500 m. In deep water, remote controlled vehicles or manned diving systems are required for subsea operation.

2.2 J-Lay Method

This method is a relatively new technology and good for very deep water beyond the limit of the S-lay method. Pipes are laid in vertical or near-vertical orientation with a specially designed pipe support tower and a very short vertical stinger. The pipe string is suspended near vertically through the water depth and bend horizontally in the sagbend immediately adjacent to the seabed.The required tension in this method is much lower than that of S-lsy method and can be estimated from the flooded pipe weight through the water depth. Because of the single vertical welding and NDT station, multi-joints of pipes are pre-assembled prior to mobiliztion to offshore. To support the near vertical pipeline, specially desigened J-lay collars are attached at the end of pre-assembled multi-joints of pipes. The J-lay collars support the whole pipe string during the installation, thus eliminating the mechanical pipe tensioning system used for conventional S-lay vessels. The J-lay collars can be also functioned as buckle arrestors and for buckled pipeline recovery in deep water. Detailed descriptions of J-lay operational systems and techniques can be found in recent technical papers.[8)9)14)]

Dynamic positioning is the common system for station keeping and the lower thrust in an essential requirement. The minimum required thrust depends on pipe diameter, allowable sagbend strain, and submerged pipe weight. It should be noted that the required horizontal thrust for dynamic positioning is almost independent of water depth. The required thrust can be estimated from the pipe bottom horizontal tension to maintain the allowable stress/strain in the sagbend.

Experience obtained on both J-lay and S-lay methods by McDermott International using the same pipe size in the same water depth indicates close parity. The S-lay method was about 18% faster than J-lay method. However, J-lay method required 16% fewer weld repairs.[15)] The average installation rate of 0.8-1.2 km is possible currently. The J-lay method has potential to reduce cost, provided that the pipe can be joined very fast in a vertical single welding station. Currently, research is in progress to develop a fast system for welding pipe in a vertical configuation[16)] and a fast NDT using ultrasonic inspection. Using J-lay method, the static and dynamic analysis of 610 mm diameter pipeline installation in water depth of 3525 m are undergoing and will be published in the near future by the author.

2.3 Reel-Barge Method

The reel-barge method uses a continuous

length of pipe coiled onto large diameter reels in which the pipe bends plastically. Assembly of the pipe string is done onshore, and nondestructive testing is completed prior to coiling the pipe. Because fo coiling, small diameters and heavy wall thickness are required to avoid pipe flattening. The pipe can be installed by uncoiling the pipe from its reel as the barge moves forward. The pipe leave the ree-barge through a straightener and a tensioner and down an adjustable steep ramp. The pipe span behind a reel-barge is essentially identical to the span behind a J-lay barge. Laying operation can be performed with high speed, thus dynamic positioning system is preferred rather than multi-point anchor system. Two types of reel-barges are in use : the vertical reel and horizontally mounted reel. The vertical reel has more advantage in deep water opration, since pipe string can be discharged from the top and does not requir a large stinger and thrust force.

The permanent bending strain of 2% is acceptable with this method. If the bending procedure involves successive bending and straightening, the maximum plastic strain is not to exceed 1%.[17] The residual ovality due to the plastic bent in the process of spooling and straightening must be accounted for determining wall thickness with the collapse criteria. In offshore Brazil, a 254 mm diameter pipeline was laid in 720 m water in 1992 and a 324 mm pipeline was laid in 905 m water in 1994. In Gulf of Mexico, a 356 mm pipeline will be installed in 1800 m water depth in 1996.[18] The maximum size of 406 mm diameter pipe is possible with this method.

2.4 Tow Method

One of the promising methods for installation of pipelines in the deeper parts of the area are probably the various towing techniques. The tow methods require relatively small vessels for transportation of long pipe strings to the installation site. The pipe strings are fabricated at onshore facilities or on offshore barges in shallow water. In addition to the tow vessel, a holdback vessel is used for control of the floating pipe string. This methods is good for short flow lines, insulated pipelines, and remote areas where mobilization of the laybarge costs substantially. Four tow methods have been developed and commercially implemented since 1975.

Surface tow uses floatations to support the pipeline at the water surface. The transported pipe strings are connected on site and lowered onto the seabed. This methods requires a relatively low towing force, but the pipe strings are towed under the wave action.

Below-surface tow uses floatations to support the pipe string below significand wave action. Pipe stringe are lowered to reduce wave action and spar bouys are generally used to limit the amount of surface motion transferred to the pipeline. This method also has applied for the arctic pipe installation by towing the pipe string under the ice.[19]

Off-bottom tow is similar to the below-surface tow, but the pipe string is close to the seabed. In deep water, this method is preferred over surface tow method due to the diffculties of lowering pipe string and controlling the required buoyancy. Few buoyancy tanks are attached to the pipe string and lengths of chains are suspended from the buoyancy tanks. Pipe string is suspended at a pre-determined design height off the seafloor by keeping balance of buoyancy tank and suspended chains. In case of pipeline crossing or other obstuctions, pipe string configuration can be easily changed by increasing the hold-back tension.

On-bottom tow method requires well known tow route, since the pipe string is in contact with the sea floor except the pulling head. Route considerations affect the coating design, stability, tow vessel size, and an optimum length of towed segment. This method is good for severe weather conditions and does not require a hold-back vessel. In very deep water, on-bottom or off-bottom tow is preferred for short lines (less than 10 km), provided that a make-up site and tow route can found clearly.

3. PIPE STRESS DURING INSTALLATION

3.1 Static Pipe Stress

The pipe stresses during the installation by laybarges are usually higher than the stresses induced during the life of pipeline. The stresses on the pipe are hoop, axial, bending, and torsional stress. Hoop stress is from the internal or external pressure and axial stress is from the lay tension and external pressure. Bending is the dominant stress for the installation and torsional stress is negligible. The important prameters on pipe stresses are pipe weight, lay tension, water depth, barge ramp radius, and stinger length. The total pipe stress is usually calculated using the von Mises or maximum distortion energy formula.[10] Various stress formula related to offshore pipeline installation can be found.[20]

In the overbend, the stresses are due primarily to the curvature imposed by the support rollers, so that the safety is directly assured by maintaining the radius of the pipeline. The pipe stress is increased if the overbend radius is decreased or the pipe weight or tension is increased. The pipe stress is very sensitive to the adjustment of support rollers due to the local bending effect. If the stinger is floating type, a careful buoyancy distribution should be calculated to achieve a desired stinger curvature.

In the sagbend, the pipe stresses are primarily functions of the tension and bending stiffness, pipe weight, and length of the pipe span. Pipe stress is increased if the pipe weight or water depth is increased, and if tension is decreased. Tension is the most important parameters to control the sagbend stress. The sagbend radius is assured by the tension and always greater than the tension divided by the unit submerged pipe weight. The capacity of the tensioning system of the laybarge is directly related to the water depth limit.

There are three points where the pipe curvature is not restricted and damage could occur easily. These are (1) at the stern of the barge, where the motion of the laybarge and stinger could lead to a misalignment between the laybarge and stinger, (2) at the stinger tip, where the pipe stress is extremely sensitive to the elevation of the stinger tip and pipe tension, and (3) at the maximum curvature in the sagbend, where the pipe has less tension near the seabed. Unfortunately, these are the points at which dynamic stresses are most significant.[21] Points (1) and (2) are critical in S-lay method and (3) is critical in J-lay method.

3.2 Dynamic Pipe Stress

The dynamic pipe stresses are due primarily to the relative motion of the laybarge and stinger imposed by the wave and current force. The fluctuations of the tension in the pipes are directly related to the laybarge motion and are monitored by the tensioner control system. To decide a limit seastate for laybarge operation, accurate dynamic stresses should be analyzed with response amplitude operators (RAO) of the laybarge. The RAO values should be calulated with considering the mooring pattern of the barge and stiffness of the suspended pipe string,

In the overbend, the pipe stress at the stinger hitch or stern roller increases substantially when the stinger rotates downward relative to the laybarge. The stress at the stinger tip is very sensitive to the motion of the stinger. If the movement of the stinger tip is sufficient to cause the pipe to bend sharply, the stress increases singnificantly. The stinger tail depth must be positioned within the allowable envelop. The dynamic behavior of the large size pipeline is even worse if the laybarge is provided with a floating stinger instead of a rigid one.[22]

In the sagbend, the pipe stresses are due primarily to change in the pipe tension resulting from the surge motion of the laybarge. The sagbend stresses are also induced by external hydrostatic pressure and dynamic loading due to environmental conditions. Most of the dynamic pipe stresses are due to the plane motion of the laybarge(surge, heave, and pitch).

3.3 Nonlinear Pipe Stress

The linear stress-strain relation is valid up to the proportional limit stress of the pipe. The proportional limit depend on the material grade and 80% of the specified minimum yield strength (SMYS). Once the pipe stress exceed the proportional limit, a nonlinear stress-strain including ovalization effect should be used. The pipe strains beyond the proportional limit are very sensitive to the stresses or bending moments.

The stress-strain relation can be expressed in the following forms ;

Needleman/Hutchinson relation

$$\sigma = \sigma_p \cdot \left(n\frac{\varepsilon}{\varepsilon_p} - n + 1 \right)^{1/n}, \quad \varepsilon \geq \varepsilon_p \qquad (1)$$

Ramberg-Osgood relation

$$\varepsilon = \frac{\sigma}{E}\left[1 + 3ovr7\left(\frac{\sigma}{\sigma_{0.7}} \right)^{N-1} \right] \qquad (2)$$

where σ_p , ε_p are stress and strain at the proportional limit,

$E = \sigma_p / \varepsilon_p$ is the Young's modulus,

n and N are strain hardening exponents, and $\sigma_{0.7}$ is the stress corresponding to a secant modulus of $0.7 \cdot E$.

Equation (1) permits stress to be written as a function of strain or strain as a function of stress. The best set of values for σ_p , ε_p and η can be calculated with experimentally determined stress- strain curves. The stress cannot be expressed as a function of strain with equation(2).

The more useful form for application is the moment-strain relation and can be expressed in the following forms;

Ramberg-Osgood relation in Shell's Formula [23]

$$K = M/B + (K_b - M_b / B) \cdot (M / M_b)^n$$
$$B = EI, \quad n = 16 - 0.07D/t, \qquad (3)$$
$$M_b = \sigma_y D^2 t \cdot (1 - 0.002D/t), \; K_b = t/bD^2$$

K and M are curvature and moment of the pipeline, B is the flexible rigidity,

D and t are outer diameter and wall thickness of the pipe, b is strain reduction factor,

σ_y is specified minimum yield strength (i. e. stress at 0.005 bending strain)

Non-dimensional Ramberg-Osgood relation[10]

$$K/K_y = M/M_y + \alpha \cdot (M/M_y)^{\beta}$$
$$Ky = 2\sigma_y/ED, \; M_y = 2I\sigma_y/D \qquad (4)$$

Equation (3) is an empirical formula developed by Shell and widely used in offshore industries.

Equation (4) is a non-dimensional form of Ramberg-Osgood equation used in the program OFFPIPE. M_y and K_y are yield moment and yield curvature. OFFPIPE input data requires either a pair of α and β or two pairs of $M_i^* = M_i/M_y$ and $K_i^* = K_i/K_y$ at two points of the moment-strain curve. Once the moment-strain are calculated by a lab test or API curves, then the coefficients α and β or M_i^* and K_i^* in equation(4) can be determined by using the curve fit method. Alternatively, the coefficients α and β can be determined so that equations (3) and (4) match almost same moment-strain curves. This technique will be much easier with

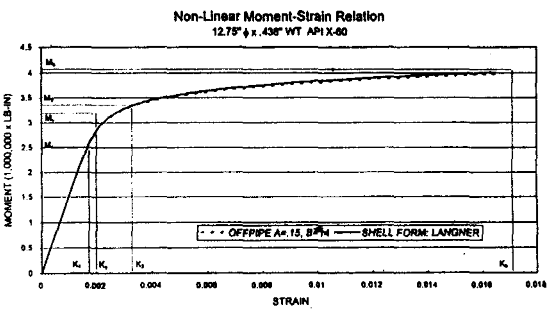


Fig. 2 MOMENT-STRAIN GURVE, 324mm OD × 11mm WT, X-60 PIPE

a computer aided graphic method. OFFPIPE will lead to easy converged solutions with a pair of α and β than with two pairs of M_i^* and K_i^* Fig. 2 shows the moment-strain curves for a 324 mm diameter, API X-60 pipe. In Fig. 2, curves by equations (3) and (4) are almost same for given coefficients α and β and various points, are indicated in the sample calcuation in Appendix. It should be noted that M_y and K_y are not on the moment-strain curve and extension of linear line correspond to the pure bending strain of 0.002.

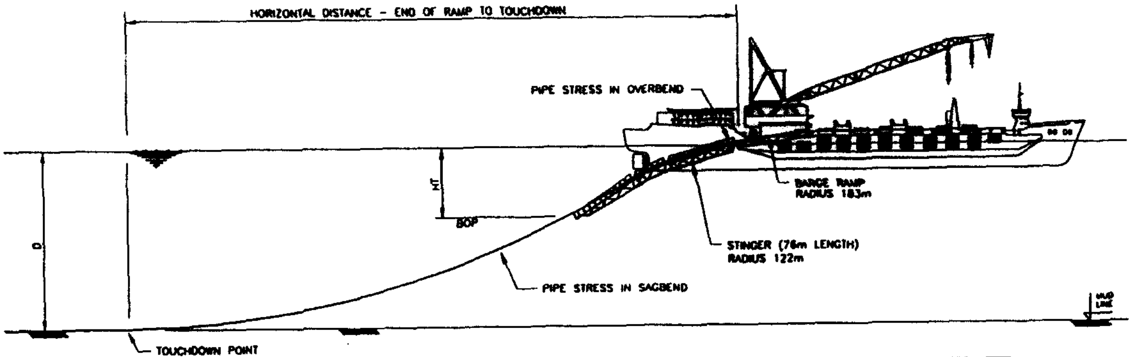
4. PIPELINE INSTALLATION

4.1 Normal Lay

Once the pipelay start-up mode is finished by a selected initiation method,[11] the pipelay mode is changed to normal lay mode. Stress or strain analyses, linear or nonlinear analyses, static or dynamic analyses should be performed according to the project specifications. The pipelay configurations are pre-determined with specified ranges of tensioning schedule so that the stresses are kept below the specified limits and acceptable departure angles are obtained. This method is well developed with many years experiences except very deep water installation. Ultimate goal of the analysis is to reduce the lay tension. The lower tension will eliminate many potential problems during the installation. The strain criteria may reduce the installation tension and considerably increase the depth limit of the laybarge.[24] Fig. 3 shows a typical normal lay method and tensioning schedule.

4.2 Davit Lifting

The davit lifting operation is a special pipelay mode used for pipeline buckle recovery or tie-in with riser pipelines. The lifting is done according to a pre-determined procedure and is carried out in several steps of pipeline elevations. Most of the laybarges have several davits for this purpose. This operation is very difficult for a heavy pipeline in deep water. The minimum number of davits must be selected through a rigorous analysis. The critical pipe stress occurs when the pipe head is located from sea bottom to one-third of water depth. To reduce the pipe stress at critical elevations, the laybarge moves forward direction with a pre-determined distance to impose axial tension components in the



PIPE WALL THICKNESS (inches)	COATING THICKNESS CORROSION (inches)	COATING THICKNESS CONCRETE (inches)	SUBMERGED WEIGHT (lb/ft)	WATER DEPTH D (feet)	STINGER TAIL DEPTH AT LAST ROLLER-Ht (feet)	MAX. PIPE STRESSES (% SMYS) OVERBEND	MAX. PIPE STRESSES (% SMYS) SAGBEND	TENSION AT BARGE (kips)	HORIZONTAL DISTANCE STERN TO TOUCHDOWN (feet)	PIPE GAIN (feet)
0.562	0.016	0.0	16.5	1290	(-)110.5	80.27	17.50	55	2343.1	429.7
0.562	0.016	0.0	16.5	1200	(-)110.5	79.56	18.20	50	2160.3	404.5
0.562	0.016	0.0	16.5	1100	(-)110.5	78.05	19.20	45	1959.0	373.0
0.562	0.016	0.0	16.5	1000	(-)110.2	78.05	18.30	45	1934.3	310.5
0.562	0.016	0.0	16.5	900	(-)117.6	78.05	17.43	45	1905.2	267.6
0.438	0.016	1.0	22.7	800	(-)110.5	81.01	25.22	45	1425.7	267.1
0.438	0.016	1.0	22.7	700	(-)110.4	80.84	27.03	40	1203.5	229.3
0.438	0.016	1.0	22.7	600	(-)110.2	79.00	29.47	35	1141.1	191.7
0.438	0.016	1.0	22.7	500	(-)117.9	78.91	32.02	30	1010.4	154.3
0.438	0.016	1.0	22.7	400	(-)110.3	76.95	50.34	20	761.9	130.9
0.438	0.016	1.0	22.7	320	(-)110.0	75.94	62.05	15	631.5	101.3

Fig. 3 NORMAL LAY & TENSION SCHEDULE, 324mm OD, X-60 PIPE

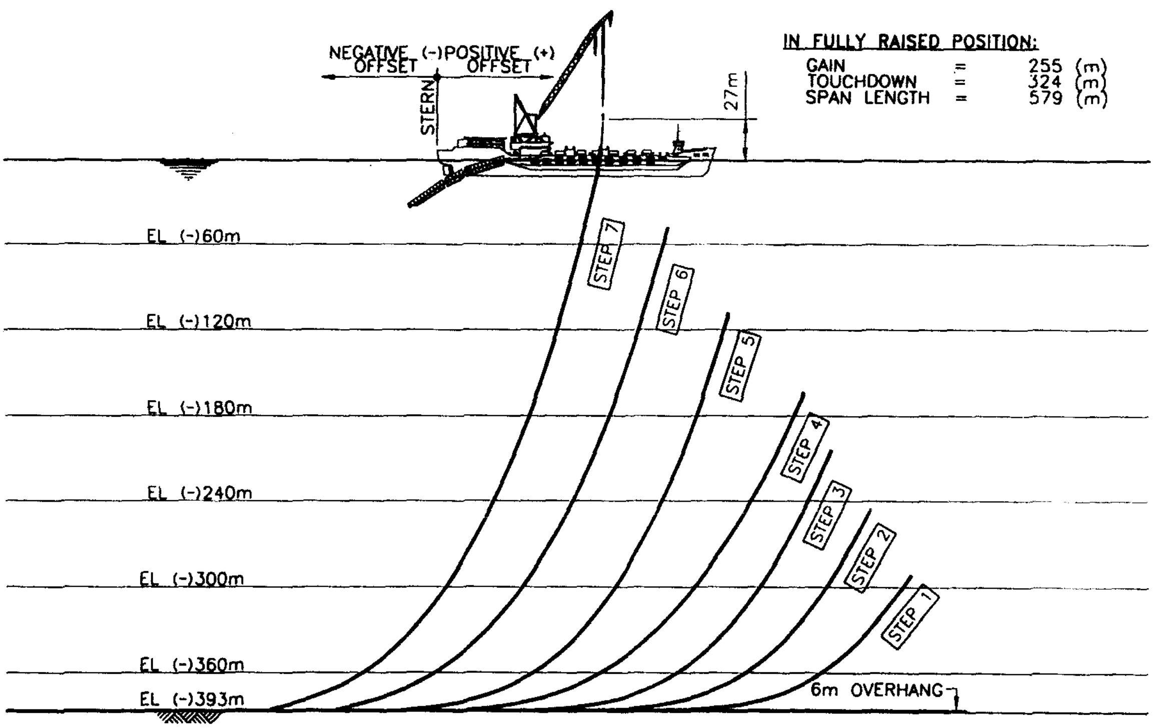


Fig. 4 WET SINGLE POINT LIFT, 324mm OD × 14mm WT, X-60 PIPE

STEP	CABLE LENGTH (m)	BARGE OFFSET (m)	LINE TAKE-UP (m)	ELEVATION OF CONNECTIONS (m)		TOUCH DOWN (m)	LIFT POINT REACTIONS (kN)	PEAK STRESS (% SMYS)
				ATTACHMENT POINT	END OF PIPE			
SETUP	421	0	0	-393	-393	0	0	0
1	380	+150	41	-302	-297	219	178	63
2	309	+60	40	-256	-250	236	222	75
3	257	0	52	-213	-207	254	267	57
4	215	-30	42	-173	-167	235	334	52
5	150	-120	65	-117	-111	229	356	62
6	63	-180	65	-55	-49	324	423	58
7	30	-210	55	-3	+3	324	467	60

Fig. 5 WET SINGLE POINT LIFT, 324mm OD × 14mm WT, X-60 PIPE

pipeline, then the barge moves backward as the pipeline is lifted above a certain height. Fig. 4 demonstrates a 324 mm pipe in 396 m water depth can be lifted using a single davit even for a flooded pipe and Fig. 5 shows the davit lifting parameters in several steps.

The davit lifting analysis with OFFPIPE used to be very tedious with several davit lines and required a lot of simulations to get the converged solutions. By varying the length of the first davit line and specifying the tension in the remaining lines, most of the davit lift can be performed with several trial error bases. Moreover, a striking improvement can be achieved by providing a slacking phantom davit line and varying tension in all the davit lines. This technique will lead to converged solutions very easily for any davit lift analyes.

4.2 Abandonment and Recovery(A&R)

This operation is required when the pipelay is interupted by a rough seastate or an equipment failure. The pipeline is laid down to seabed using a cable attached to the pipehead and A&R winch which is taking the transferred tensions from the tensioners. The main goal of this operation is to put the pipehead on the seafloor without overstressing the pipe span. This is done by moving the barge forward with a pre-determined distance and then decreasing the tension by several steps. The analysis of this operation should be checked at several different pipe elevations.

Once the weather allows the pipelay operation, the pipe is recovered using the reversed order of laydown. The recovery is also required if a pipe buckle is detected during the installation In case of a dry buckle, there will be a small change in pipe tension stinger. If a wet buckle occurs, the rapid flooding of the pipe will increase loads on the stinger and tensioner. This would likely result in failure of the stinger or slippage of the pipe through the tensioner. For this reason, a contingency procedure for an emergency A&R operation is essential for deep water laying when the flooded pipe weight exceeds tensioning capacity. The critical phases of the recovery are the pipe pullhead is close to seabed and the damaged area is on the overbend curvature. The stress analysis with OFFPIPE requirs good initial values of sagbend span lengths for converged solutions. Fig. 6 shows a typical A&R operation.

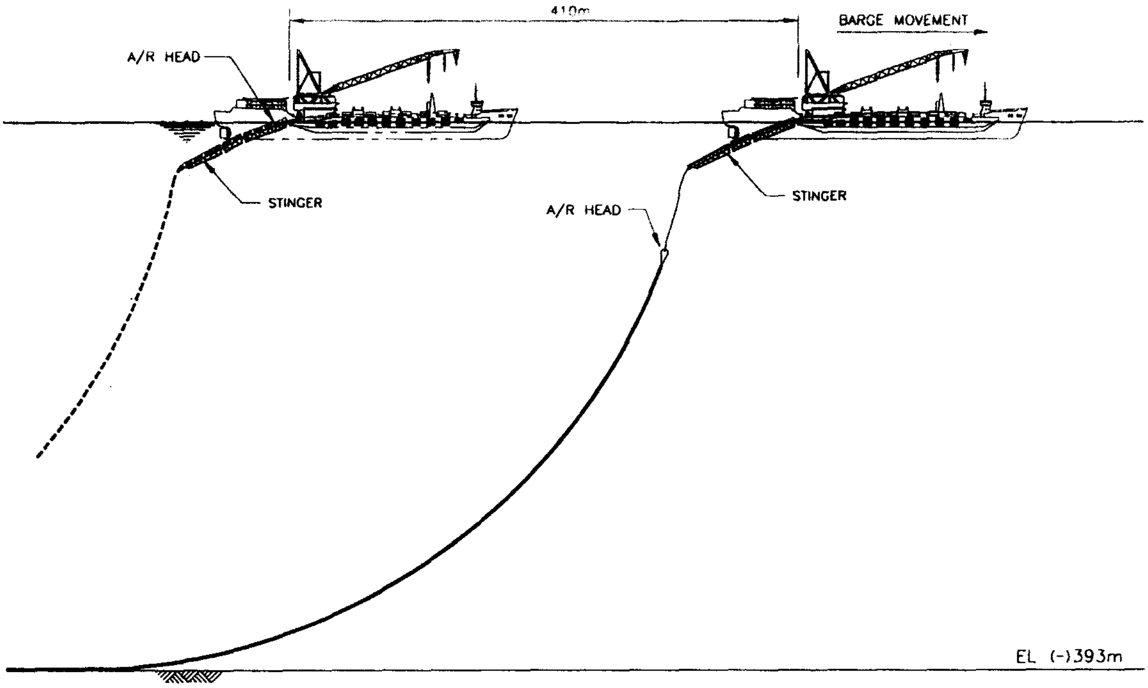


Fig. 6 ABANDONMENT & RECOVERY IN 393m WATER

CONCLUDING REMARK

As a result of the literature survey, many installation analyses, and field experience, the following conclusions can be drawn.

1. S-lay method with upgraded laybarges is preferred for the installation of long piplines in water depth up to 1000 m and is capable of laying small size pipes in deeper water. For extending the depth limit, increasing tension and mooring capacity is most important in S-lay.

2. J-lay method is preferred beyond the S-lay method if towing or reeling methods are not feasible. J-lay is the only available method for long, large diameter pipelines in very deep water. For extending the depth limit, thrust modification is critical in J-lay.

3. Tow method is good for short lines in 1000 m water or deeper and its application for the special purpose projects is very wide.

4. Reel method may be the lowest cost installation option in deep water, within the constraints bounded by pipe size, length, and water depth.

5. Rigorous strain analysis should be performed with nonlinear moment-strain relation, and ovalization effect for deep water pipelines under the combined load of bending and pressure.

6. The goals of the offshore pipeline installation analyses are deciding minimum lay tension in normal lay, minimun numger of davit lines and pulling force in davit lift, and optimum operation procedures in A&R.

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Appendix : Sample Calculation of Nonlinear Data for OFFPIPE pipe : 324 mm OD x 11.33 mm WT, API X-60

D = 0.423 m, t=0.01113 m, E = 2.067E11 N/m^2, I = 1.337E-4 m^4,
$K_y = 2\sigma_y/ED$ = 1.236E-2 m^{-1}
$M_y = 2I\sigma_y/D$ = 3.423E-5 N-m
D/t = 29.11, b=1.0, $K_b = t/bD^2$ = 1.061E-4m^{-1}
$M_b = \sigma_y D^2 t\ (1-0.002D/t)$ = 4.552E5 N-m
n = 16-0.07D/t = 13.962, B = EI = 2.772E7 N-m
Arbitary selected moments
M_1 = 2.829E5 N-m = 2.5E6 lb-in, M_2 = 3.734E5 N-m = 3.3E6 lb-in
$K_i = M_i/B + (K_b - M_b/B)(M_i/M_b)^n$, $\varepsilon_i = K_iD/2$ for i = 1,2
Using above data
K_1 = 1.032E-2 m^{-1}, ε_1 = 1.67E-3, K_1^* = 0.835, $M1^*$ = 0.826
K_2 = 1.911E-2 m^{-1}, ε_1 = 3.09E-3, K_2^* = 1.545, $M1^*$ = 1.082
For OFFPIPE input,
1) Pairs of (K_1^*, M_1^*), ($K_2^*M_2^*$) can be used or
2) α = 0.15, β = 14 can be selected to match equations (3) and (4).