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Challenges of Lowering a Live Subsea Buried Gas Pipeline by 6m

N. I. Thusyanthan, Offshore Installation Services (OIS) Ltd, K.A.J. Williams, Vision Oil and Gas, T. Selwood, Offshore Installation Services (OIS) Ltd, P. Smith, NCS survey Ltd, S. Jegandan, INTECSEA, D.J. Robert, Monash University

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Abstract

There are hundreds of kilometers of subsea pipelines around the world, forming a network for the extraction and transportation of oil and gas products. When near shore subsea pipelines cross shipping channels to ports, these pipelines can limit the size of the ships that enter the port. This is because the shallow burial depth of the existing pipeline can prevent any additional dredging required to deepen the shipping channel to accommodate larger vessels. An attractive solution under such circumstances is lowering the pipeline section throughout the width of the channel so that the channel can be deepened. The option of shutting the line down or installing a re-routed new line has cost implications. However, the alternative of lowering a pipeline while it is fully operational has engineering risk, operational challenges and the offshore industry is not very experienced in such projects. This paper presents a case study of such a key project where a 16" gas pipeline was successfully lowered from -3m to -9m below the seabed whilst fully operational. The live gas pipeline was crossing a shipping channel and was buried at 3m below seabed. In order for the port to expand and allow bigger vessels to enter the port, the shipping channel needed to be deepened. Thus the pipeline was required to be lowered a further 6m for a stretch of 350m where the pipeline crosses the shipping channel. The lowering operations had to be carried out whilst the pipeline was fully operational as it was a 70km pipeline with key supply. This paper presents detailed overview into engineering challenges and operational issues faced on the project. The paper discusses all the stages of the project, risk assessments; integrity assessment for pipeline lowering; geotechnical assessment of trench stability; detailed pipeline lowering stress assessment; pre-operational planning; pipeline survey and pipeline lowering operation; post lowering integrity assessment. The pipeline lowering was successfully completed to meet the project requirement after 14 lowering passes. This successful lowering of a live gas pipeline by 6m is considered to be world's first such lowering. Recommendations on how a pipeline lowering project should be approached, assessed and executed are presented in this paper.

Introduction

As economic demand for cost effective and larger container vessels is growing, ports around the world are expanding to accommodate larger vessels. Near a port in Southeast Asia, a 16"gas pipeline was buried 3m below seabed where a shipping channel crossed it in a water depth of about 10m. The port authorities wanted to expand and accommodate larger ships. In order to accommodate these larger ships, the channel needed to be dredged, thus the pipeline was required to be either re-routed or lowered to below the depth of dredging. The project requirement was that a 350m section of a 16inch top of pipeline (TOP) needed to be below 19m from Lowest Astronomical Tide (LAT) as shown in Figure 1. This was a lowering of about 6m from the existing pipeline profile. The pipeline was 70km in length and was supplying gas to key cities thus could not be stopped. After an initial cost assessment, the re-routing option was dismissed due to high cost and the timeline required to design and install a new pipeline section. The pipeline lowering option had engineering risks and operational challenges as this scale of pipeline lowering of a fully operating subsea pipeline by 6m had never been carried out before.

The initial stage of the project was to undertake an engineering feasibility study and risk assessment to evaluate whether such a lowering was possible from pipeline integrity point of view. This assessment resulted in positive outcome but with a number of restrictions required to control risk. The following sections provide insight into the detailed engineering assessment and how the risks were managed in this project to successfully complete the lowering operations.

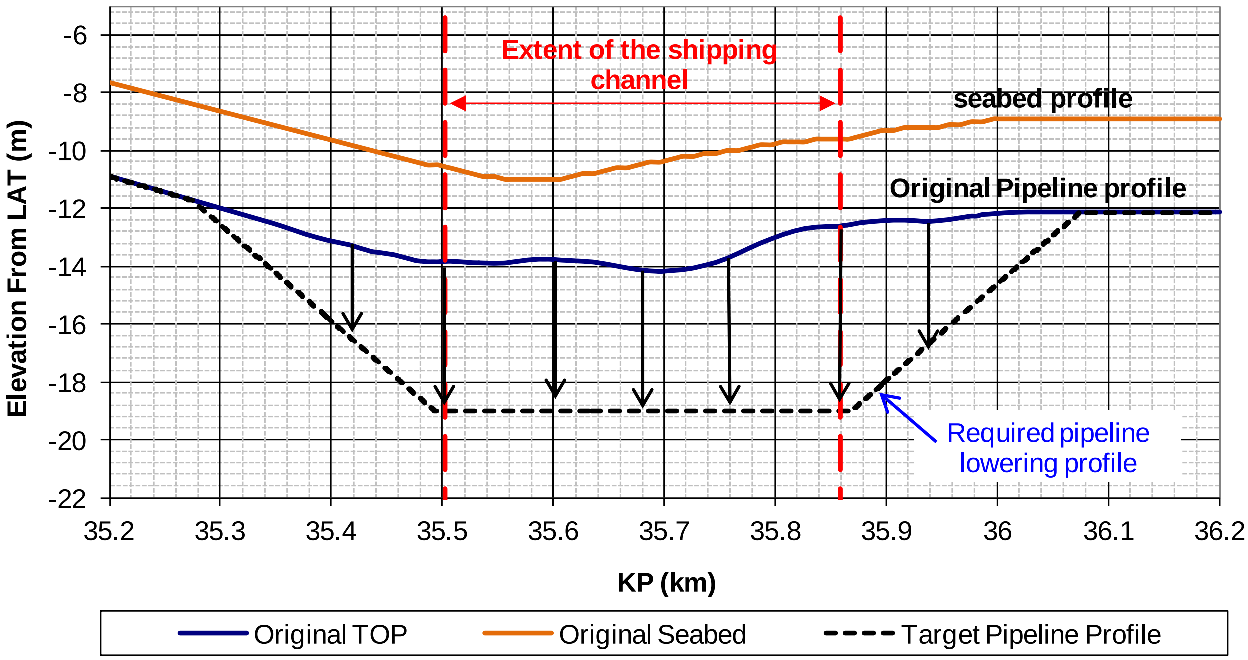


Figure 1: Pipeline's original elevation profiles compared with target elevation profile.

Project Overview

This project involved detailed engineering assessment to determine what could be performed safely and develop lowering procedures and implementation of these operational procedures. The consequence of damage to pipeline during the lowering operation would be severe, thus risk assessment and proper mitigation measures were key to the success of this project. In order to keep the paper concise, only an overview of the project details and key issues are presented in this paper. The key project stages are summarized below:

- **Risk Assessment & Engineering Feasibility study**
  - Risk identification and mitigation
  - Pipeline data and allowable stresses
- **Detailed Engineering Assessment**
  - Pipeline integrity (allowable step height & slope angle for pipe lowering, FE assessment)
  - Seabed trenching (trenching tool, geotechnical data, trench geometry & stability)
- **Pre-operational Planning**
  - Plan for the lowering operation sequence
  - Pipeline Survey and lowering by Mass Flow Excavator tool
- **Pipeline Lowering Operation**
  - Pipeline lowering operations
  - Pipeline Survey and Pipeline Integrity assessment after every lowering pass

Details of each of these stages are provided in below sections.

Risk Assessment & Engineering Feasibility Study

An engineering feasibility assessment was carried out in parallel with a risk assessment for the pipeline lowering operation. All the pipeline properties and operating conditions were reviewed to evaluate the existing stress levels and condition of the pipeline. Table 1 presents the pipeline data and operating conditions of the pipeline.

The main aims of the risk assessment were;

- To identify all the hazards and to carry out a risk assessment for hazards affecting the pipeline and the trenching vessel
- Evaluate the consequences, if there was a loss of containment during the pipeline lowering operation
- Identify control and mitigation measures to reduce any "High" risks to "Low"

Table 1 Pipeline properties and operating conditions

Pipeline properties		
Parameter	**Units**	**Value**
Outer Diameter	mm	406.4
Wall Thickness	mm	12.7
WT Manufacturing (negative)	mm	1.27
Corrosion Allowance	mm	1
Steel Grade	-	API 5L X52
Steel Manufacturing Process	-	Seamless
Steel Density	kg/m^3	7850
Steel Modulus of Elasticity	GPa	207
Steel Poisson's Ratio	-	0.3
Coefficient of Thermal Expansion	1/°C	1.17×10^{-5}
Specified Minimum Yield Strength (SMYS)	MPa	359
Specified Minimum Tensile Strength (SMTS)	MPa	455
Pipeline operating conditions		
Parameter	**Units**	**Value**
Pressure	bar	34.1
Content Density	kg/m^3	79.7
Pipeline operation temperature	ºC	27.8
Pipe Specific Gravity with concrete coating		1.4
Environmental properties		
Parameter	**Units**	**Value**
Water Depth along the required lowering section	m	9.5 to 10.5
Sea Water temperature during installation	ºC	22.5 to 24
Maximum Sea water temperature	ºC	27.8

The initial phase of risk assessment exercise is to identify all the potential hazards and their consequences associated with the pipeline lowering operations. A Hazard Identification Study (HAZID) and risk assessment review meeting was held. Some of the "High" risk items identified in the project risk assessment are shown in Table 2. The key was to determine what mitigation measures could be developed to reduce the project risks and how it could be ensured that all these identified measures were undertaken during the operation to reduce all the identified risks to an acceptable level of risk category. As each project is unique, what is acceptable can change from project to project. Thus, constant negotiations and discussions with all parties involved in the project and local authorities would be critical at this stage in the project. It is to be noted that a number of mitigations on this project relied on the accurate survey of the pipeline before, during and after the lowering process. Thus the survey operation was identified as key for the project from the onset.

Table 2 A small extract from Risk Assessment table

HAZARD	HAZARD EFFECT	CONSEQUENCE	PROBABILITY	RISK	MITIGATION/CONTROL	Reduced RISK
Loss of vessel DP system	High loads on umbilical, etc. Possibly applying loads on to the pipeline from the tooling. Breach caused by tooling impact on pipeline.	CATASTROPHIC	MEDIUM	HIGH	Needs discussion with contractor about weak links, umbilical lengths and contingency measures Needs discussions with vessel operator on DP tolerances, back-up, contingency, etc. Vessel to sit outside of gas release calculated \`boil area\`	MEDIUM Subject to satisfactory discussions with contractor and vessel operator, operation can go ahead but requires due care and attention. Need to verify safety features are working at mobilisation.

HAZARD	HAZARD EFFECT	CONSEQUENCE	PROBABILITY	RISK	MITIGATION/CONTROL	Reduced RISK
Loss of gas containment due to trenching issues creating over stress as specific girth weld micro fracture	High loads on pipeline around anomaly soil areas, etc. Possibly applying greater loads to the pipeline. Breach caused by stress on pipeline. ESDVs take time to close and pipeline gas volume releases at pressure	CATASTROPHIC	MEDIUM	HIGH	Needs to control the trenching operation to control bending stress and minimize risk of failure, leading to full bore rupture. Trenching procedure should be controlled to achieve a probability of pipeline failure of 'very low'. Needs discussion with contractor regarding contingency measures and gas boil area for vessel stability and gas plume ignition – working in Safe Zone of gas boil area Unless the probability of pipeline failure is reduced to 'very low', reduction in pressure during trenching becomes necessary to reduce the gas release rate, avoiding 'Catastrophic' consequences.	MEDIUM Subject to satisfactory discussions with contractor and vessel operator, operation could go ahead but requires due care and attention on calculated `boil area` and ignition issues relative to pressure vs boil area size for vessel stability and gas plume ignition Need to verify safety features are in place at mobilisation
Deteriorating weather conditions ; Squalls	Vessel experiences excessive environmental movement. Device damages pipeline due to heave comp failure(e.g. dent, gouge or concrete damage) containment breach; Vessel Stability	CATASTROPHIC (leak) MAJOR (damage)	MEDIUM	HIGH	Maintain awareness of weather conditions (e.g. 5 days look ahead) Establish procedures for weather contingency/abandonment and standby / recovery situations (Safe Position / Area) Vessel to sit outside of gas release calculated `boil area` where possible.	MEDIUM (leak) LOW (damage)
Vessel not following pipeline track	Equipment damages pipeline (e.g. dent, gouge or concrete damage)	MAJOR	MEDIUM	HIGH	The trenching tool not kept close to the pipeline The trenching tool location to be controlled accurately in relation to the pipeline	LOW Digger must be kept clear of pipe

The Engineering Feasibility Study was undertaken to evaluate whether the lowering operation was feasible while ensuring that the pipeline integrity was not compromised at any stage in the pipeline lowering operation. The feasibility study was mainly to evaluate whether the pipeline stresses can be maintained below an acceptable limit during the lowering operations. This allowable stress limit was based on pipeline properties, operating conditions, current status of the pipeline, Engineering Critical Assessment (ECA) and guidelines from design standards.

The following allowable stress limits are given in ASME B31.8 were used as a basis:

- Longitudinal Stress : 80% of the SMYS
- Combined Stress : 90% of the SMYS

The ECA assessment of the original design was based on API 1104, assuming Crack Tip Opening Displacement (CTOD) to be 0.254mm. As API has changed since the 2005 edition used at the design phase, an alternative fracture assessment was performed following BS 7910, which is also in-line with the recommendations of DNV OS F101. The recommendation of ECA assessment was that the longitudinal stresses in the pipeline should be limited to 70% SMYS. Thus, the pipeline lowering operation was possible only if the pipeline stresses induced due to the lowering operation superposed on the existing pipeline stresses is below the 70% SMYS (251MPa). The pipeline lowering operations induces pipeline stresses due to two factors; tensile stresses due to stretching of the pipeline; bending stresses during the lowering operations. The stretching induced tensile force on the pipeline was estimated to be 980kN for the lowering to -19m LAT. The existing pipeline stresses were calculated based on the pipeline vertical profile and the operating conditions. As the pipeline was originally jetted and lowered, zero residual lay tension (RLT) was assumed. Figure 2 presents the calculated longitudinal stresses along the pipeline length. The tensile force induced stresses were superposed to the existing longitudinal stresses. A stress concentration factor (SCF) of 1.13 for the concrete coating was included in stress calculations. It is evident from the results presented in the graph that there is sufficient stress capacity before the 70% SMYS limit is reached. Thus, it was concluded that the pipeline lowering operation is feasible provided that the pipeline shape (and thus bending stresses) were monitored during the lowering operation and the longitudinal stress limited to 251 MPa (70% SMYS).

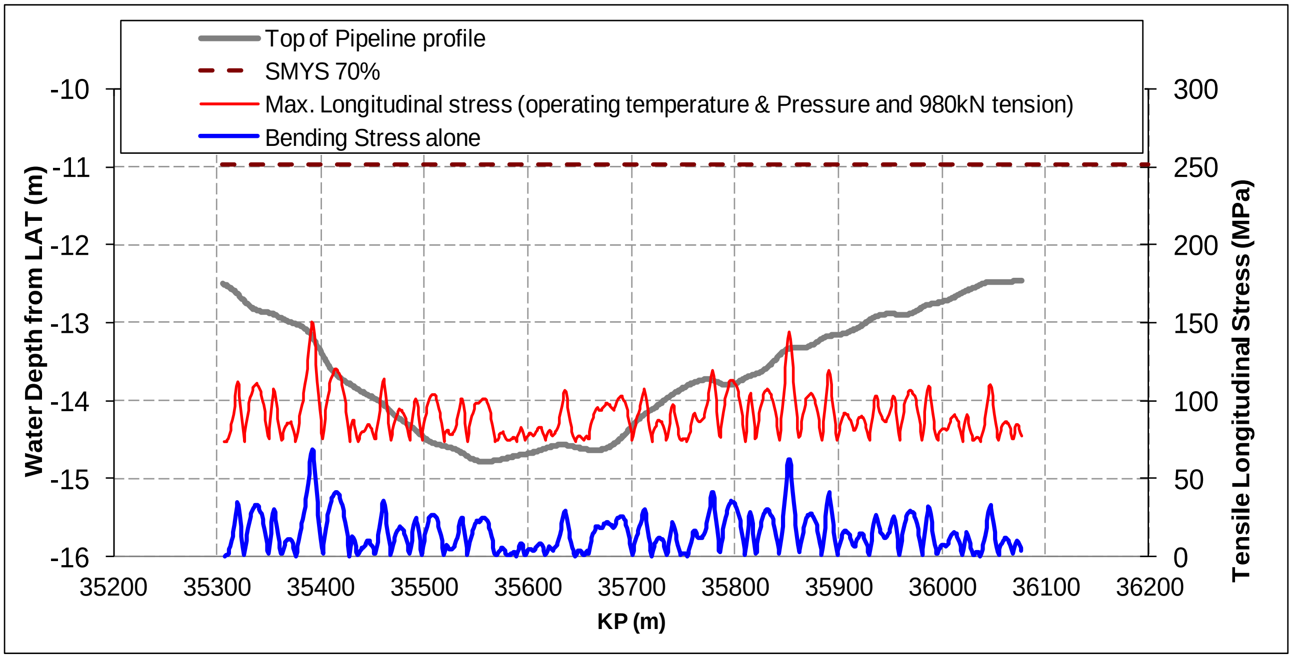


Figure 2: Pipeline stress assessment results from engineering feasibility study

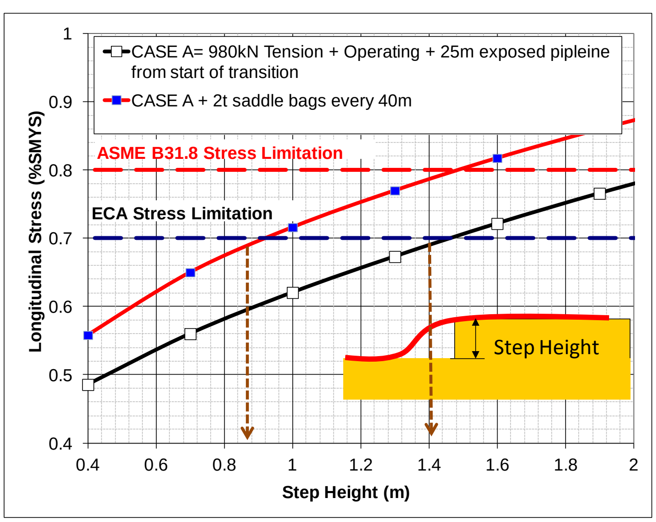
Detailed Engineering Assessment

As the feasibility study concluded that the pipeline lowering operation was possible without compromising the pipeline integrity, a detailed engineering assessment was undertaken in order to finalize the pipeline lowering procedures. The detailed engineering assessment investigated two aspects;

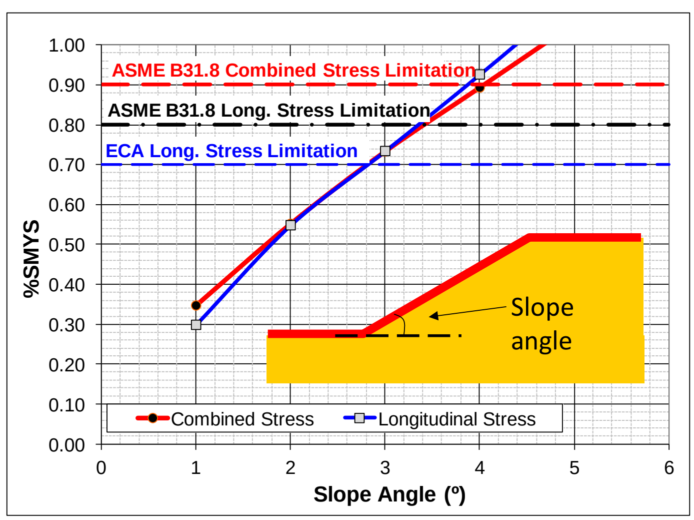
- Pipeline integrity - Allowable step height, slope angle for pipe lowering, Finite element analysis
- Seabed trenching - trenching tool, geotechnical data, trench geometry and stability

Pipeline Integrity

Pipeline integrity needed to be ensured throughout the pipeline lowering process. Thus, parametric studies were undertaken to identify the allowable step height and slope angle for pipeline lowering operation. Figure 3 presents the results of the parametric study. The allowable step height and slope angle for pipeline lowering were limited by the fact that the longitudinal stresses needed to be limited to 70% SMYS. An installation temperature of 22.5°C and operating temperature of 27.8°C was used in these analyses. The assessment results concluded that the critical depth of lowering per pass is 1.4 m, if no additional weights (saddle bags) are used and 0.85 m, if additional weights (saddle bags) of up to 2t submerged weight, at a spacing of no less than 40 m, are used to mitigate floatation.



(a) Allowable step height for pipeline lowering



(b) Allowable slope angle for pipeline lowering

Figure 3: Parametric study results

The following factors were also considered as critical for the pipeline lowering operations

1. Pipeline floatation potential
2. Allowable free span length

The pipeline specific gravity (SG) with and without the concrete coating was 1.40 and 1.04 respectively. Thus, if the concrete coating were to fail during the lowering operation, there was a high risk of pipeline floatation. Furthermore, as the pipeline lowering operation was planned to be carried out by Mass flow excavator, the fluidized soil around the pipeline could increase the floatation potential. It was concluded that the SG of the pipeline needs to be increased to 1.7 if floatation was observed. It was planned that saddle bags (2t each) would be placed at regular intervals of 40m over the pipeline to mitigate the floatation if concrete coating damage or pipeline floatation was observed. The saddle bag weight and spacing were calculated such that the vertical deflection of the pipeline would be limited to 10cm. The allowable free spans during the pipeline lowering operation was assessed with a dead load of 10 kN/m on top of the pipeline, to account for the additional weight provided by the backfilling material. Based on the results of the assessment, the allowable free span had to be limited to 14m to ensure pipeline stresses are within allowable limits (70% SMYS).

A detailed finite element simulation of the pipeline lowering operation was undertaken in ABAQUS to evaluate the pipeline integrity throughout the lowering operations. The bottom of the trench was adjusted at each increment to account for the amount of soil that would be cut by the jetting tool. In these analyses, saddle bags with a submerged weight of 2t at 40 m spacing were considered. The pipeline was modelled using ABAQUS PIPE21 elements. The following steps were carried out in FE assessment;

- Restrain axially both pipeline ends (25m away from the start of transitions)
- Apply the pipeline weight (including saddle bags every 40m)
- Activate the seabed friction
- Apply internal pressure and the differential temperature
- Adjust seabed profile to represent lowering operation
- Apply the weight of the backfilling material
- Assess the pipeline stresses

A series of sensitivity analyses were also performed to assess the influence of the following parameters:

- Soil parameters (Soil stiffness / Axial Friction / Soil dead load)
- Installation temperature and operating temperature
- Pipeline exposed section outside the trench
- Loss of wall thickness due to corrosion
- General arrangement of saddle bags (weights) to prevent floatation (pitch / weight)

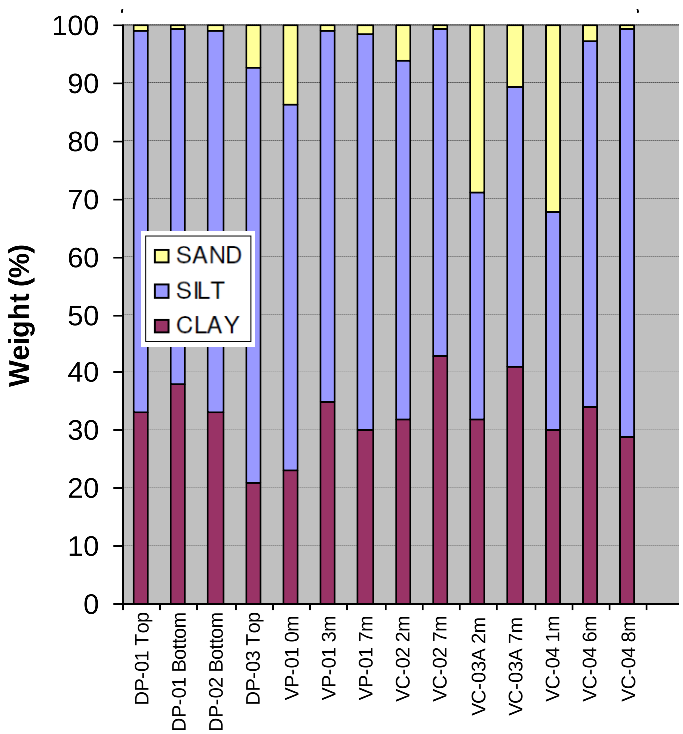
The full pipeline lowering FE assessment and sensitivity analyses results were used to conclude the following for the pipeline lowering operations.

1. The pipeline has to be exposed at least 25m ahead of the location start of transition at both ends.
2. The transition of the pipeline is to have a 2 degree (1 in 30 slope) slope angle.
3. The maximum depth of lowering in a single pass should be limited to 0.85m, if weights are used to mitigate floatation.
4. Maximum allowable free span of 14m with assumed 10kN/m backfill weight on the pipeline.
5. It is recommended that the pipeline is surveyed after each lowering pass to confirm that the above limitations are met or take any necessary mitigation action.

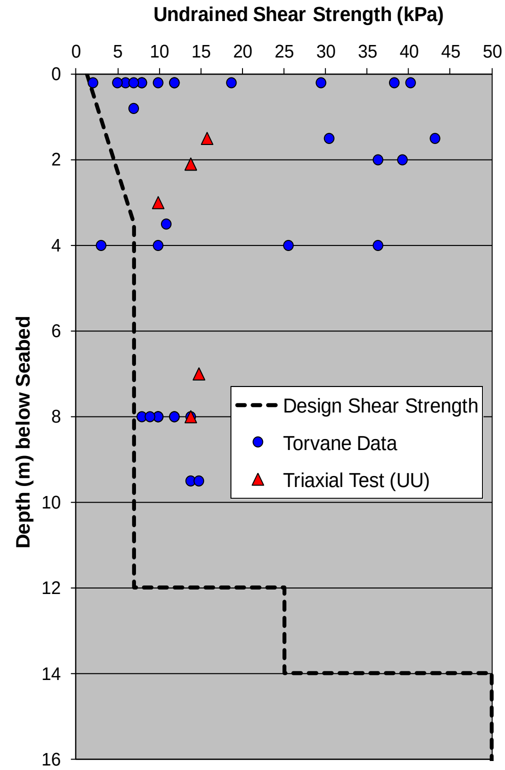
Seabed Trenching

There are three main aspects to the seabed trenching; trenching tool, geotechnical data, trench geometry and stability. The trenching tool was selected as the Controlled flow excavator “T8000”. The tool develops 600 horse power and produces water flow rates of up to 8000 litres per second and water jet speeds up to 8 metres per seconds. The tool was selected because of the “Non-contact method of excavation” providing high levels of safety for operation near pipeline and speed, and ease of mobilisation.

Knowledge of geotechnical properties of the seabed are critical for pipeline lowering operation as both the rate of trenching and the stability of the trench depend on the seabed soil properties. The geotechnical data at the site was available from 3 drop cores and 4 vibro-cores about 150m away from the pipeline location. Figure 4 summarizes the geotechnical data that was available at the start of the project. It is evident from the results that the seabed soil consists of 21%-42% clay and the rest was mainly SILT but with up to 30% SAND content in few of the samples. This suggests that while the soil behavior is predominantly clayey, silty behavior is also to be expected. The plasticity index ranged from 40% to 70%, and showed that the soil is borderline between being classified as clay or silt based on the plasticity chart.



(a) Soil classification based on BS5930



(b) Undrained shear strength (kPa) vs depth

Figure 4: Geotechnical data

The trench geometry needed to be such that the pipeline can be lowered from about -3m below seabed to -9m below seabed. The stability of the trench was important as any failure of trench during pipeline lowering operations could be risky. The slope stability can be assessed in two ways depending on the soil conditions and the duration for which the slope is required to be stable. These are;

- *Undrained stability* (short term stability) assessment based on shear strength of soil
- *Drained stability* (long term stability) assessment based on the friction angle of the soil

The undrained stability is for short term assessment in CLAY while the drained stability is for long term assessment in CLAY or short term assessment in SILT or SAND. As the site soil conditions cannot be fully classified as CLAY or SANDs, both "undrained" and "drained" stability assessment were performed. The trench geometry was assessed using SLOPE/W software to provide a factor safety of 1.3 for undrained stability and drained stability. Figure 6 presents the design trench geometry resulting from the above assessment.

Pre-operational Planning

This project potentially carried a high degree of risk and hence a detailed and thorough pre-operational planning was essential for the success of the project. Pre-operational planning included;

- Risk management
- Plan for the lowering operation sequence
- Pipeline Survey and Pipeline lowering by Controlled Flow Excavator tool

The risk management strategy involved mitigating all risks to acceptable level, by following the determined safe lowering process and preparing for identified hazards, such as saddle bags being kept ready for deployment in case pipeline floatation was observed. An observation ROV was on board and on standby during the project. The pipeline lowering operation was planned in phases. The initial phase was to dredge and expose the pipeline so that the start of the transition for the pipeline could be identified. Figure 5 shows a schematic of the pipeline lowering requirement along the length of the pipeline. It is to be noted that the figure is not to scale and the pipeline is shown as flat for illustration only. Once the pipeline was exposed for 25m at both the ends, the lowering was planned in 12 passes. For each pass, the target lowering per single pass was selected as 0.5m. This is so that any tolerances due to survey accuracy, excavation tool and wave height effects can be safely accommodated without compromising the pipeline integrity.

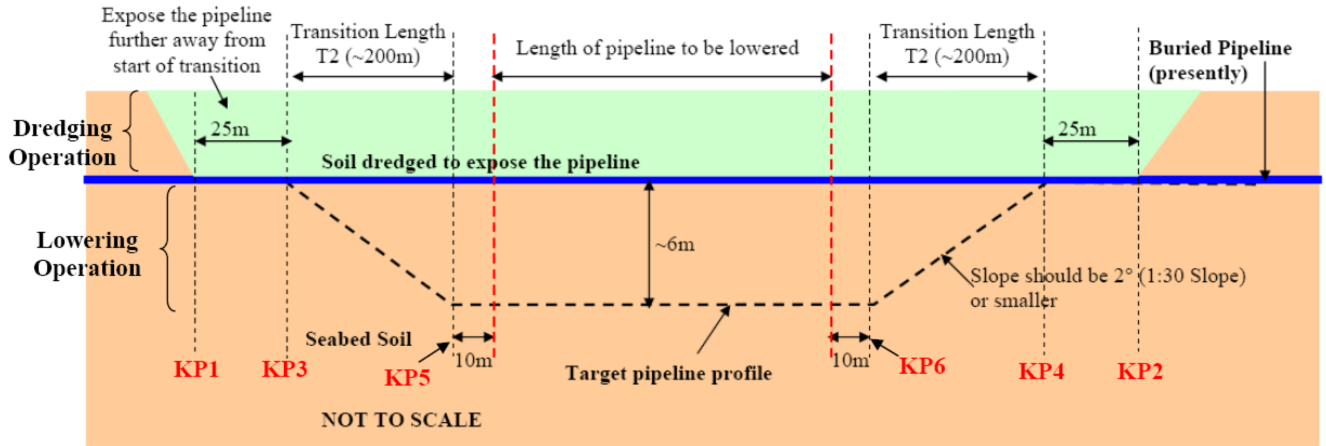


Figure 5: A cross sectional sketch along the pipeline length showing key KP points (transition lengths, target pipeline lowering & slope angle)

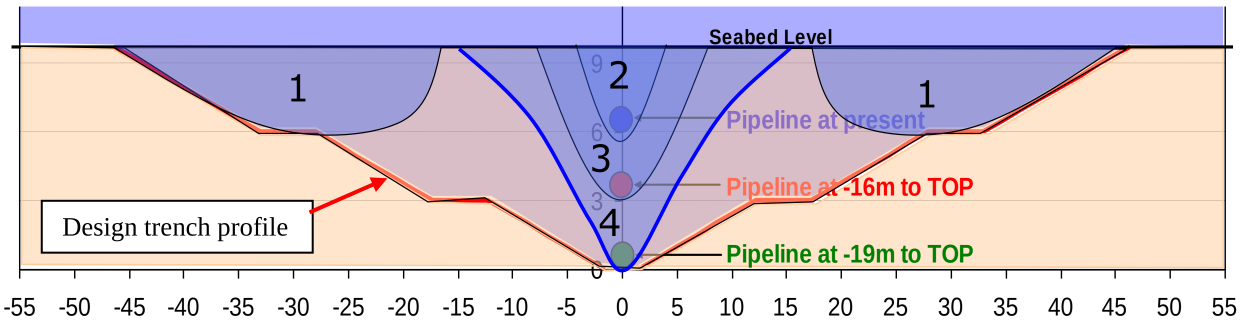


Figure 6: Cross section view of the pipeline and trench profile

Pipeline Lowering Operation

An initial bathymetric survey was undertaken at the site to evaluate the site topology prior to any excavation work. This was carried out by a multi-beam system (MBES) mounted on an over-the-side pole on the vessel. A sub-bottom profile survey was then undertaken at 50m intervals to locate the pipeline and thus determine its original vertical profile of the pipeline. The excavation tool CFE T8000 was used for both the mass excavation of soil to expose the pipeline and then to lower the pipeline gradually. After the pipeline was exposed at the ends (25m sections), the seabed was excavated using T8000 tool to reflect the design trench as shown in Figure 6, but not all the regions were trenched as it was realized that once region marked (1) was excavated, the pipeline lowering could be performed by excavation of regions (2) to (4) with real time survey. The areas shown as (1) were excavated as phase one excavation. The regions 2, 3 and 4 show the sequence of the excavation during pipeline lowering which was considered as phase two excavation. Excavation of regions 2 to 4 were carried out in 14 passes as the pipeline was lowered incrementally. It is to be noted that region (1) infilled due to a storm event soon after excavation but this did not affect progress as the infill was not a concern for trench collapse.

Real-time survey of both the pipeline and tool location was required to ensure that the pipeline lowering was being carried out as planned. This was achieved by real-time visualization of data from MBES heads mounted forward and rear of the excavation tool. This enabled the location of the pipeline, the trench profile and the tool to be viewed real-time by the tool operator. Figure 7 shows such a view of real time monitoring during one of the pipeline lowering passes. This real time monitoring was vital to ensure that the pipeline was lowering gradually and that the CFE tool was maintained sufficient distance away from the live gas pipeline.

After each of the pipeline lowering passes, a detailed pipeline survey (top of pipeline fix survey) was undertaken and the survey results were used to assess the pipeline stresses. A pipeline integrity memo was issued after each of the lowering passes and the memo either gave the operational crew permission to proceed with the next lowering stage or provided instructions as to what areas of the pipeline needs to be lowered further to ensure that a single location does not become a stress concentration point. The pipeline integrity memo after each pass presented a pipeline stresses as shown in Figure 8. The figure shows the top of pipe (TOP) and the associated longitudinal pipeline stresses (maximum and bending stresses alone). Figure 9 presents the bathymetric survey of the site near the final stages of the pipeline lowering. Figure 10 presents the survey data after each of the pipeline lowering passes. It can be seen from Figure 10 that the pipeline had been successfully lowered to the requirement of -19m LAT after 14 lowering passes. It is also evident that the target slope angle of 2 degrees was also achieved.

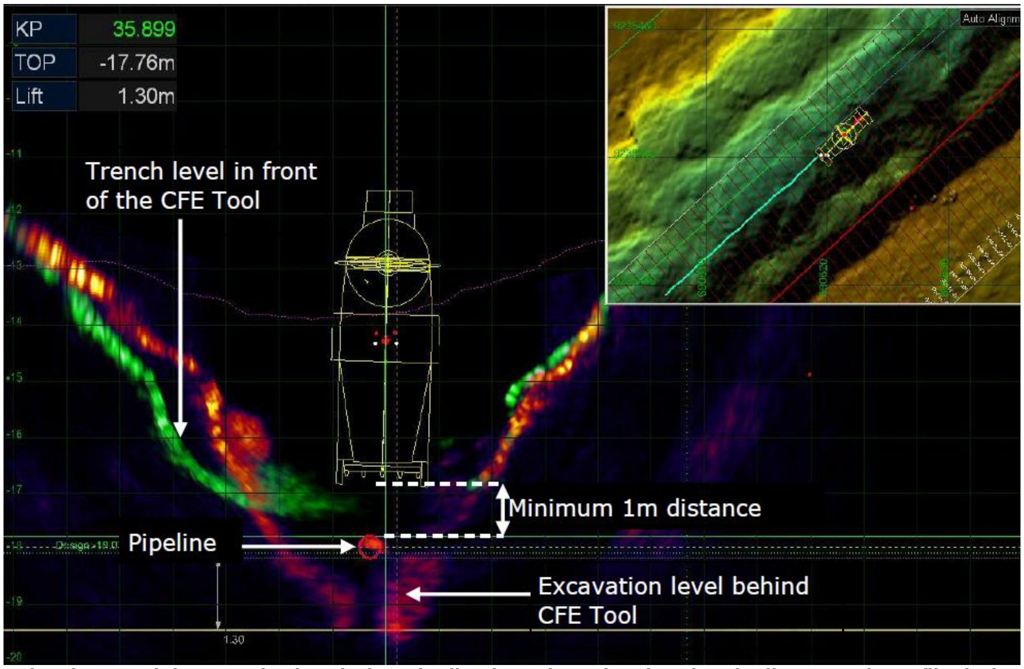


Figure 7: Screen shot from real time monitoring during pipeline lowering, showing the pipeline, trench profile during the T8000 excavation

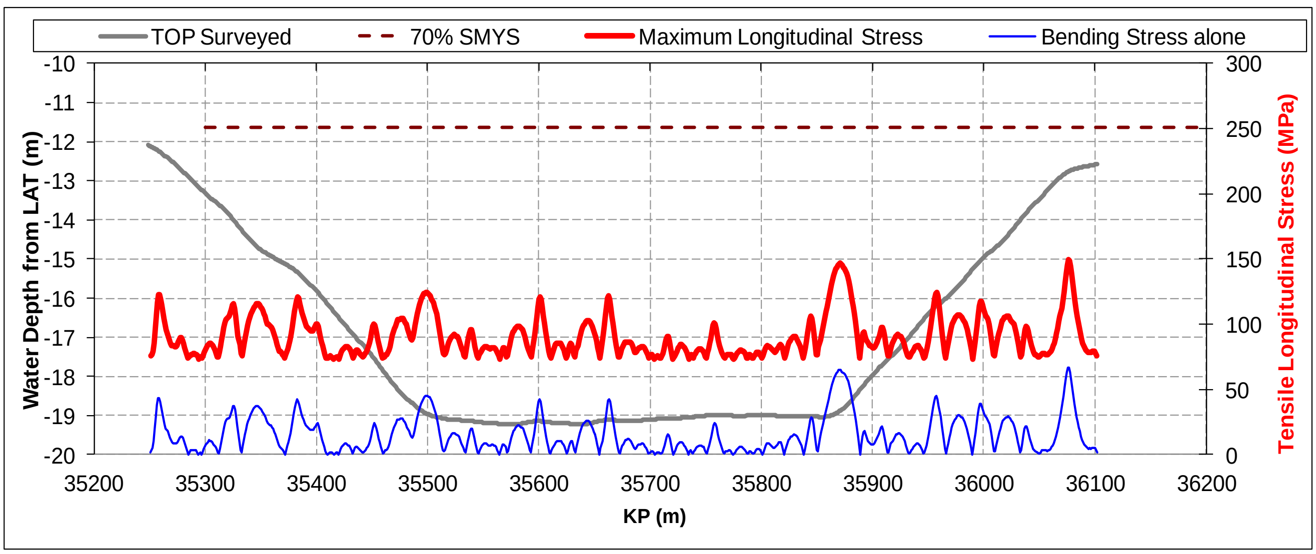


Figure 8: Pipeline stress assessment results after the final lowering pass of the pipeline.

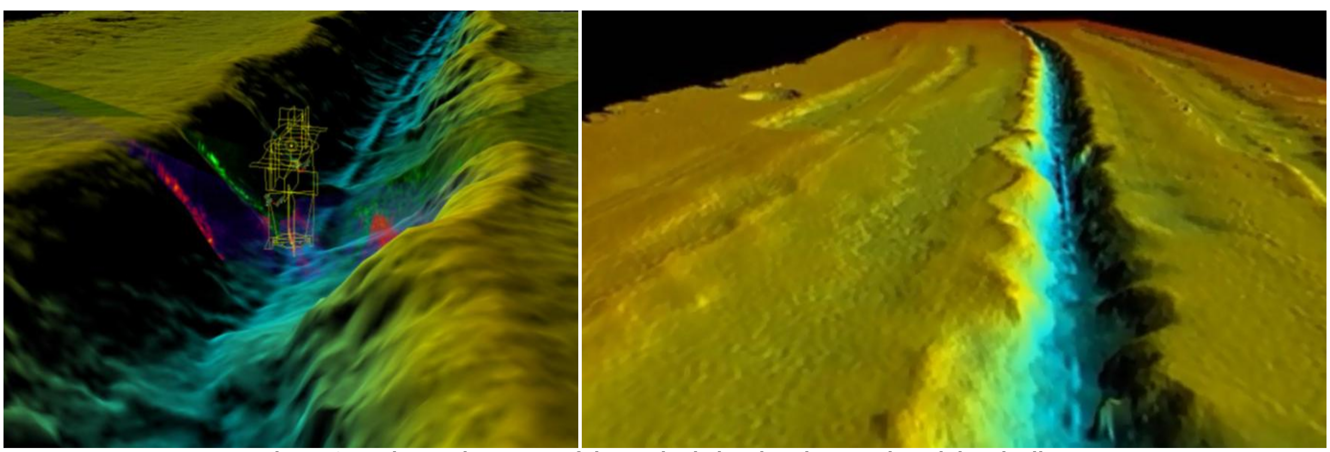


Figure 9: Bathymetric survey of the seabed showing the trench and the pipeline

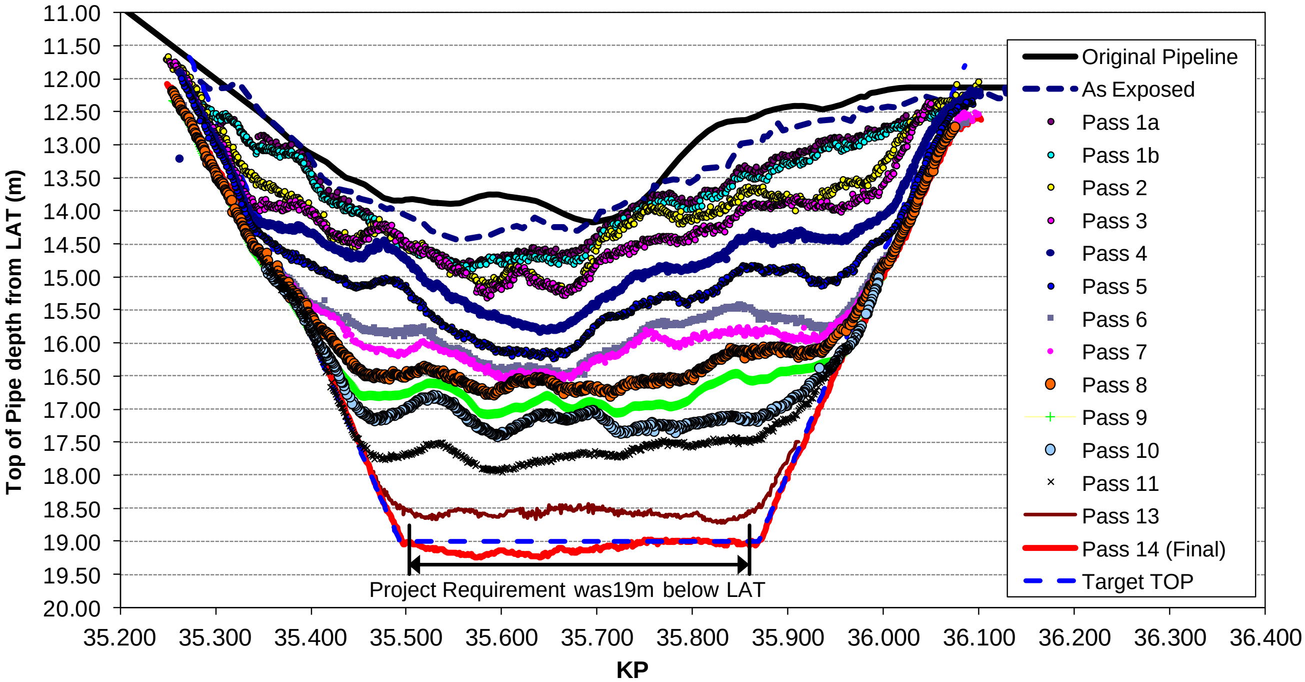


Figure 10: Pipeline survey data after each pipeline lowering pass.

Difficulties Encountered

Any project of this nature is bound to have unexpected difficulties. This project was no exception and encountered the following difficulties that caused some project delays,

1. A higher volume of shipping traffic compared to the project initial estimates limited access to the project site.
2. Infilling of excavated trench due to shipping traffic
3. The rate of trenching was very slow at some locations
4. Bad weather conditions

Recommendation for Pipeline lowering Projects

Based on the experienced gained from this project, the following sequence of steps are recommended for any future pipeline lowering projects.

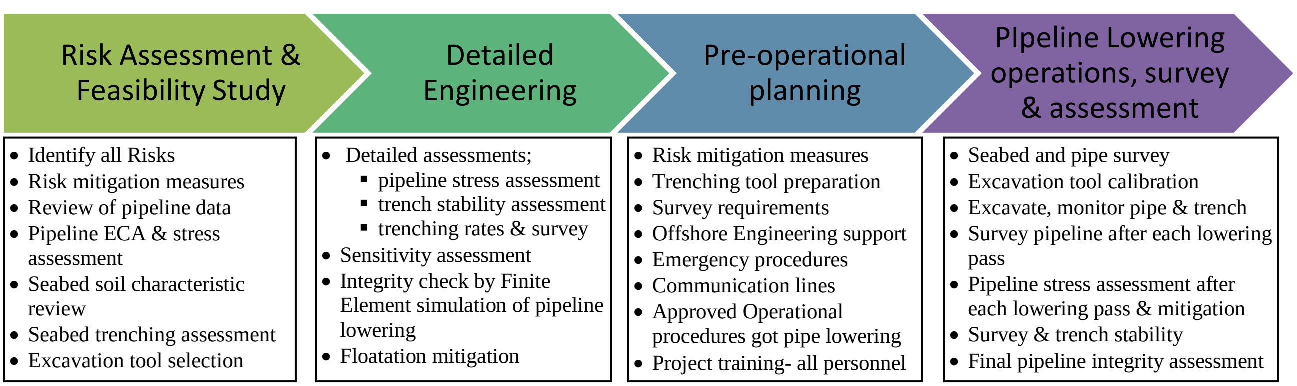


Figure 11: Recommended high level task list for Pipeline lowering projects

Conclusion

This paper presented a case study of a project where a live gas subsea pipeline was successfully lowered by 6m. Figure 12 presents the original and final pipeline profiles. The project demonstrated that with proper risk assessment, detailed engineering, operational planning, a high risk project can be successfully executed. The project requirement of lowering a 350m section of the pipeline below 19m LAT was successfully achieved. This project is considered to be the first of the kind where a live subsea gas pipeline was lowered by almost 6m. The success of this project and experienced gained in this project has waved the path for future projects. Detailed risk assessment and mitigation, through & detailed engineering assessment of the pipeline stresses and seabed characteristic, pre-operational planning and real-time monitoring, survey and assessment of the pipeline integrity were the key to the success of this project. Based on the experience and lessons learned from this project, a list of high level task list is presented in Figure 11 for future pipeline lowering projects. The pipeline lowering concept is also an effective solution for free-spans as outlined in Thusyanthan et al. (2014).

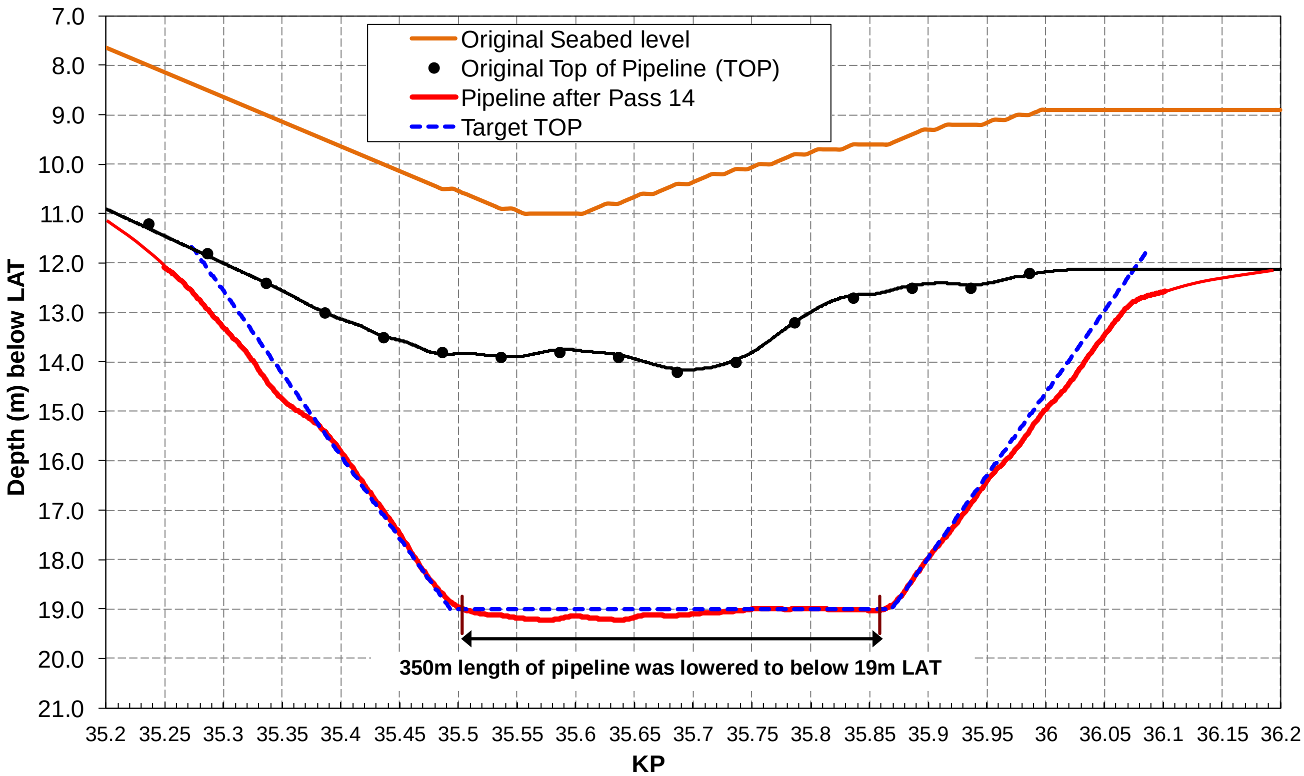


Figure 12: Original and final pipeline profiles

Acknowledgements

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