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# Pull-Back Load and Stress Analysis of Pipelines Installed By Horizontal Directional Drilling

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*A thesis submitted to offshore technology institute, university of port harcourt*
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**ABSTRACT**

This work examines pull-back loads and stresses in pipelines installed by method of Horizontal Directional Drilling, which are susceptible to buckling, stalling and outright failure. In order to predict the required pull-back forces and allowable limit stresses that would assure the integrity of an HDD pipeline, two methods of analysis were adopted. Mud density was varied from 1100 kg/m$^3$ to 1450 kg/m$^3$ to determine its effect on pull-back loads and stresses. Appropriate design criteria were applied to determine the installation loads and stresses. A versatile and user friendly Template was developed in MathCAD to aid multiple design and analysis for different case scenarios. The Template is capable of predicting a pull-back load which requires the application of safety factor ranging from 1.15 to 1.25 instead of the 2.0 in current use. A typical 24" (609.6 mm) x 685m HDD pipeline installation was simulated using this tool. The result of the theoretical pull-back load obtained was compared to actual field results. The theoretical results obtained without applying factor of safety are 68.67 ton with mud density of 1450 kg/m$^3$(PRCI) and 66.6 ton with a mud density of 1100kg/m$^3$ (L&M) while the actual field result is 74.1 ton with a mud density of 1395 kg/m$^3$. The theoretical stresses compared favorably with the actual. Finally, this analysis has created a Tool that closely predicts the pull-back loads and stresses necessary for successful pipeline installation by HDD.

**Key words:**Directional drilling, mud density, safety factor, stress, pulling load**,** MathCAD

## I. INTRODUCTION

Pipelines and pressure piping systems are essential for transportation of inflammable liquids and gases from one point to another in the petroleum and other industries. Depending on application, pipelines can vary from smaller diameters and lengths to very large diameters spanning long distances. For instance a Russian pipeline system has been reported to be as large as 1422 mm diameter straddling several thousands of kilometers (Hopkins, 2008).

In Nigeria, due to increased oil and gas exploration and production activities there has been proliferation of pipelines. These pipelines, in their course of routing, pass through railways, highways, rivers, swamps, creeks, etc., which pose some technical and operational challenges to the asset owners, the constructors and to the general public. However, the most challenging is river crossing which employs a special kind of technology called Horizontal Directional Drilling (HDD), as called Trenchless Technology.

Horizontal Directional Drilling is a method of pipeline installation employed all over the world to cross pipelines of appreciable length and diameter through deep rivers. Pipelines installed by this method are usually subjected to stresses which can alter the mechanical properties of the pipe material and this makes HDD method a difficult one and requires proper analysis of stresses, forces and soil conditions in order not to compromise the integrity of the pipeline. Before Horizontal Directional Drilling (HDD) Rig is deployed to any location (site), detailed site investigations must have been conducted. The objectives of site investigation inherent to HDD construction is determination and portrayal of the location specific aspects relevant to selecting, designing and executing the installation methodology (Hair, 1995).The complicated nature of this technology lends credence to continuous research and development of better pipelines installation methodology.

### 1.1Aim and Objectives of the Study

The aim of the study is to develop a template for predicting the safe pull-back loads and stresses required to install pipelines by Horizontal Directional Drilling.

The objectives include:

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1. To identify site parameters required to appropriately specify an HDD rig and associated equipment prior to site deployment.
2. To estimate and analyze the forces and stresses required to successfully pull pipelines back through drilled pilot holes during installation.
3. To simulate a typical 24 inch (609.6 mm) x 15.9 mm x 685 m pipeline during pull-back developed in MathCAD® Design Template and to compare the results with other existing design methods.
4. To make recommendations to improve design and installation practices for HDD pipelines.

**1.2Significance of the Study**

The correct solution of the problem presented in section 1.2 will lead to:

1. The establishment of design criteria which will account for all individual and combined forces pertinent to determining the pull-back loads and stresses in the installation of HDD pipelines.
2. Development of a design template in MathCAD® for predicting the safe pull-back loads and stresses for HDD pipelines.

## II. METHODOLOGY

**2.1 Research Design**

The research was designed to specify and analyze all applicable criteria required for Front End Engineering Design for installation of an HDD pipeline, and to develop a Template using the appropriate mathematical model that will enable computation, prediction and verification of pull-back loads and stress obtained prior to commencement of installation of the pipeline system.

The methods adopted for data collection include those obtained from recently completed HDD project, while the secondary data were obtained from theoretical analysis. The entire process has been partitioned into input, processing and output sections detailed below.

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**2.1.1 Input Data**

The input data basically involves pipeline, fluid and environmental data which include but not limited to pipeline external diameter, wall thickness, internal diameter, pipe grade, density, specified minimum yield strength, design temperature, design pressure, design factor, factor of safety, young's modulus of elasticity. Fluid data such as density, dynamic viscosity, fluid drag coefficient and environmental data such as soil coefficient of friction, soil type, borehole external diameter and soil density. The data are necessary to critically determine the feasibility of the installation and required installation loads and stresses.

**2.1.2 Processing**

The input data were processed to evaluate the loads and stresses experienced by the pipeline during installation. This was done using an established mathematical model and semi-empirical models of PRCI (1995). In the course of processing the input data, derived parameters such as pipe cross sectional area, pipe weight, borehole area, submerged weight of mud, etc., were obtained to facilitate the computations.

**2.1.3 Output Data**

Output data include pull-back loads at various sections (straight path – curved path – and straight path) of the pipeline been installed and stresses (tensile, bending and hoop) at different sections. The output data displays acceptable and unacceptable loads and stress conditions based on established criteria to ascertain feasibility of the installation with respect to project specification.

**2.2 Source of Data**

The data used for this study were obtained from theoretical and empirical analysis.

**2.2.1 Primary Data**

Primary data for 24" (609.6mm) x 685m pipeline used in the case study were obtained from a Nigerian HDD pipeline installation company. 685m is the length of River crossing. The primary data included pipeline design data, drilling fluid data and environmental data.

**2.2.2 Secondary Data**

Secondary data for the study were obtained from literature reviews of relevant previous works, while the mathematical and semi-empirical models were obtained from Design Manuals and Standards such as PRCI (1995), ASME B31.8 (2012) and ASTM F1962-99 (1999).

**2.3 Method of Data Analysis**

Two methods were used for analyses of the data viz. PRCI and L&M methods. The reasons for using these two methods are to compare their results with actual field results, in order to determine their validity and variations in results (if any). Computations were performed manually on a typical 24" (609.6mm) x 685m x 15.9 mm wall thickness (WT) pipeline based on these methods. However, the pull-back force and stress analysis of pipelines installed by HDD were analyzed using MATHCAD software. Design templates were developed to allow for multiple cases and to clearly indicate whether an allowable limit has been exceeded or not.

### 2.3.1 Simulation of the case study

A case study of a typical 24" (609.6mm) x 50km x 15.9 mm wall thickness pipeline was analyzed. The 50km is the entire length of the pipeline project. The pipeline was designed to transport gas at an envisaged rate between 100 and 300 BPD from location X to location Y. At kilometer post 8 and kilometer post 9 along the Right of Way (ROW), there is a river/swamp crossing about 681.44 m long and 12 m deep. The pipeline is required to be buried 10 m below the water. The entry and exit angles were specified at 12$^o$ and 11$^o$ respectively. The bend radius (radius of curvature) is 700m. The drilling fluid specified for the installation is a bentonite-based drilling mud. Its functions are to stabilize the borehole, return the cuttings to the surface, reduce friction between pipe wall and the borehole, cool and lubricate the drill bit. The dimensional data, material properties and drilling mud properties are as specified in Table 3.1.

Table 2.1 General Pipeline Data

| | |
|---|---|
| Pipeline Outer Diameter | 24" (609.6mm) |
| Pipe wall thickness | 15.9mm |
| Pipeline Material Grade | X65 |
| Pipeline Design Code | ASME B31.8 |
| Pipe specification | API 5L |
| Specified Minimum Yield Strength of Pipe (SMYS) | 448MPa |
| Pipe Density (Steel) | 7850kg/m3 |
| Drilling Fluid Density | 1100kg/m3 (Assumed) |
| Water Density | 1015kg/m3 |
| Soil Density | 1700kg/m3 |
| Soil Friction angle | 10$^o$ |
| Poisson Ratio for steel | 0.3 |
| Modulus of Elasticity | 207GPa |
| Installation Temperature | 25$^o$ |
| Friction factor for pipe to soil | 0.21 (Assumed) |
| Fluid Drag Coefficient | 172Pa |
| Design Pressure | 100 bar |
| Corrosion Allowance | 1.5mm |

Derived parameters such as cross sectional area of pipe, borehole area, weight of pipe in air, submerged (effective) weight of pipe, pipe buoyancy, etc, were determined.

### 2.3.2 Calculations Methods

The PRCI and L&M methods adopted for the calculation of pull-back loads and stress analyses excludes the effect of overburden (external) pressure. Loads and stresses induced on the pipeline during installation are markedly different from those experienced during service life of the pipeline, thus necessitating specific calculations and design verifications. The methods used assumed that the pilot hole has been reamed approximately 12" (304.8 mm) larger than the pipe outside diameter and that the annulus between the pipe diameter and the reamed hole is filled with drilling mud of known density. Reconsolidation of the formation surrounding the pilot hole will occur over time but if any significant formation pressure loads is exerted on the pipe during the pull-back process, it is not expected that the pipe could be pulled in at all (Heuyet al., 1995). The reason for analyzing these two methods was to check how the values obtained would vary from each other and also to validate the results with actual field result.

### 2.4 Case 1: Installation Loads and Stresses (PRCI, 1995)

The PRCI methods explain that during installation, pipelines are subjected to;

- Tension required to pull the pipeline into the pilot hole and surrounding curved sections in the hole, composed of;

- Frictional drag due to wetted friction between pipe and borehole wall
- Fluidic drag of pipe pulled through the viscous drilling mud trapped in the hole annulus
- Unbalanced gravity (weight) effects of pulling the pipe into and out of a hole at different elevations
- Bending as the pipe is forced to negotiate the curve in the hole
- External hope stress from the pressure exerted by the presence of the drilling mud in the annulus around the pipe(except the pipe is filled with a fluid at same pressure)

### 2.4.1 Method for Pulling Load Calculation

PRCI (1995) Drill Path Analysis was adopted. The entire drill path was discretized into straight and curved sections. Curved sections are of equal radius and the junction between straight and curved sections constitute the beginning of the curvature for the curved section. The computation is done in such a way that the maximum pulling loads occurs immediately the pipeline emerges from the entry point. Axial loads in the pipe during the last instance of the pull-back process are distributed along its length from entry to exit point. Total axial load is composed of individual axial loads occurring in each section of the hole due to friction between the pipe and the borehole wall plus dynamic fluid friction required to move the pipe through the viscous drilling mud. Figure 3.1 below shows HDD Drill Path Profile.

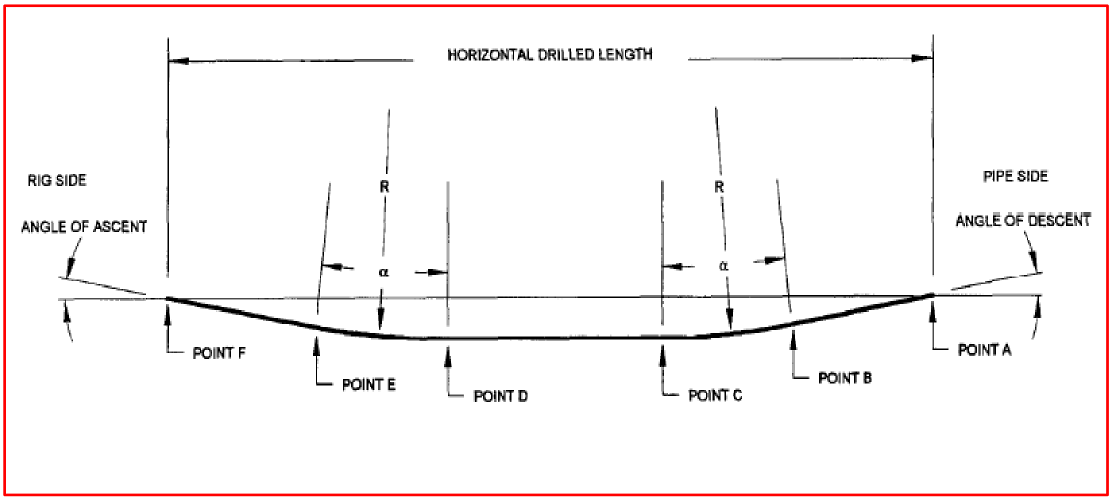


**Fig. 2.1 HDD Drill Path Profile (Source: PRCI, 1995/2008)**

- Straight section calculation

Figure 3.2 shows a straight section profile.

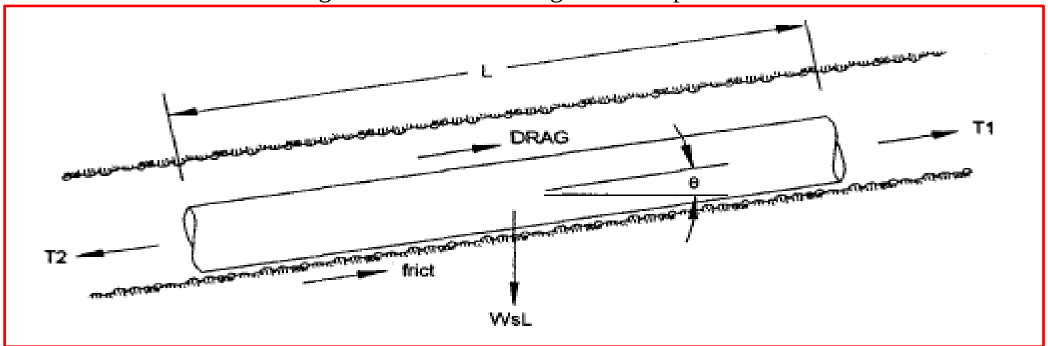


Fig. 2.2 Straight section profile (Source: PRCI, 1995)

For any straight section, the left end tension, $T_2$, is obtained from the static force equilibrium shown below.

$T_2 = T_2 + |\text{frict}| + \text{DRAG} \pm \text{Ws} \times \text{L} \times \sin\theta$ (2.1)

The ± term is resolved as follows:

- (-) if $T_2$tends downhole,
- (+) if $T_2$ tends upslope,

- (0) if the hole section is horizontal, $\theta=0$

$\text{frict} = Ws \times L \times \cos\theta \times \mu_{soil}$ (2.2)

$\text{DRAG} = \pi \times D \times L \times \mu_{mud}$ (2.3)

Where

$T_2$= Tension at the left end of the section required to overcome drag and friction (N)
$T_1$= Tension at the right end of the section (kg) (Assumed to be zero at the start)
frict= Friction between pipe and soil (kg)
DRAG= Fluidic drag between pipe and drilling mud (kg)
Ws= Effective (submerged) weight per meter of the pipeline plus internal content (if filled with water) (kg/m)
L= Length of section (m)
$\theta$ = Angle of the axis of the straight hole section relative to horizontal
$\mu_{soil}$= Average coefficient of friction between pipe and soil
D= Outside diameter of pipe (inches or meters)
$\mu_{mud}$= Fluid drag coefficient for steel tube pulled through bentonite mud; recommended value 0.05 psi (NEN 3650) – Dutch Pipeline Standard (NEN,1992)

- Curved section calculation: Figure 3.3 shows a curved section profile.

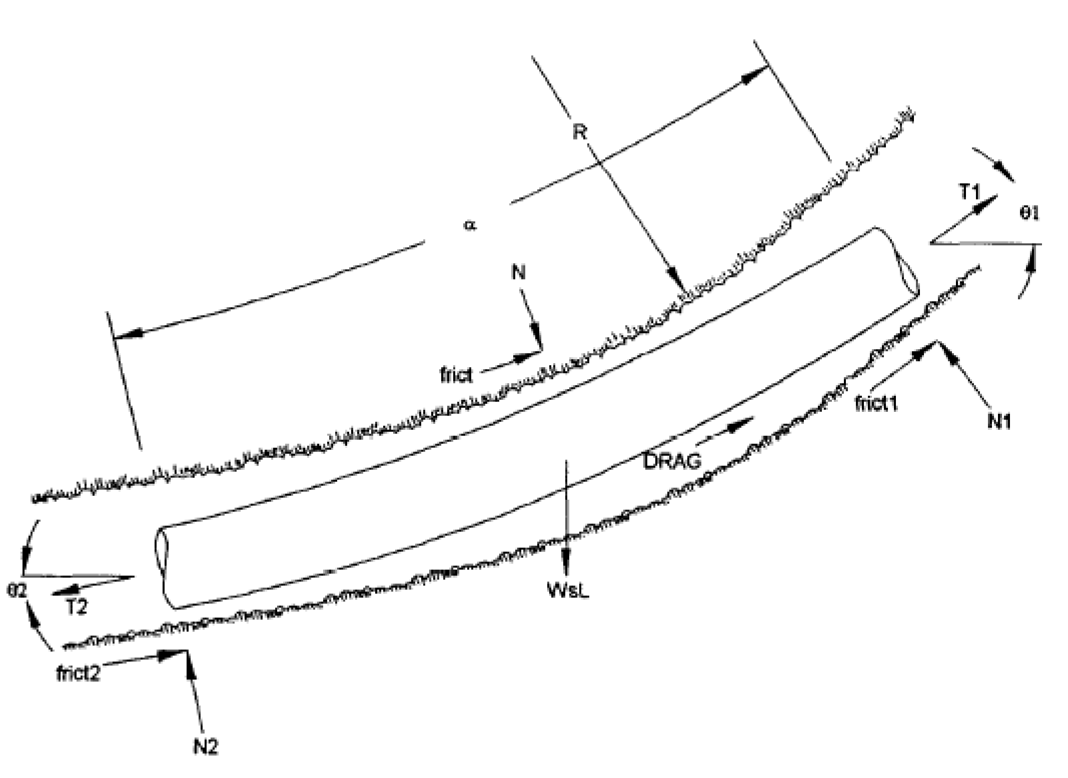


Fig. 2.3 Curved section profile (Source: PRCI, 1995)

The curved section of the drilled path profile has the same variables as the straight section with some additional variables defined as;
R= (Constant) radius of curvature of the section, m or ft
$\alpha$ = Included angle of the curved section, deg.
$\theta_1$= Angle in degrees from horizontal of $T_1$, at right end of section
$\theta_2$= Angle in degrees from horizontal of $T_2$, at left end of section
$\theta = (\theta_1+\theta_2)/2$ deg.
L is replaced by $L_{arc}=R\times \theta\times(\pi/180)$
$N_1$, N & $N_2$ = Normal contact forces at right, center, & left points, respectively
$\text{frict}_1$, frict& $\text{frict}_2$ = Frictional forces associated with normal forces at right, center, & left points respectively.

The normal forces of contact at the ends and center are obtained by idealizing each of the curved sections as a three point bending beam. Forces experienced by the beam are axial tension, plus distributed, submerged weight, Ws. Also, the reason for this modeling is to take into consideration pipe stiffness relative to curved radius. The following equations are obtained from the model.

$$h = R \times [1 - \cos\alpha/2] \quad (2.4)$$

h= displacement as the pipe is bent to fit the hole

$$N = [12 \times T \times h - (Ws/12) \times \cos\theta \times Y]/X \quad (2.5)$$

Where

$$X = 3 \times L_{arc} - (j/2) \times \tanh(U/2) \quad (2.6)$$

$$Y = 18 \times (L_{arc})^2 - j^2 \times [1 - 1/\cosh(U/2)] \quad (2.7)$$

$$j = \sqrt{E \times I/T} \quad (2.8)$$

Where
E= Young's Modulus ($2.9 \times 10^7$ psi for steel)
I= Bending moment of inertia, $inch^4$
tanh= Hyperbolic tangent
cosh= Hyperbolic cosine

The value of T is used in calculating for both N and j. The actual T value is the average of $T_1$and $T_2$, and so iterative solution is used to solve for $T_2$ for better accuracy.

$$frict = N \times \mu_{soil} \quad (2.9)$$

The assumptions are that end reactions are N/2 and end friction forces are f/2. N could be positive or negative depending on whether it acts up or downwards. However be the case, all friction values are assumed to be positive, opposing $T_2$.
The total pull-back load required to pull the entire pipe section into the reamed pilot hole is the sum of straight and curved section values.

$$T_{tot} = \sum_i (T_2 - T_1), \text{for i sections} \quad (2.10)$$

It is worthy of note that the Fluid Drag Coefficient of 0.05psi recommended by NEN 3650 (NEN, 1992) was used by PRCI (1995), but after much reviews and experiences over the years, they decided to use 0.025psi with the reason that it gives a better result (PRCI, 2008). So this analysis has also utilized same value as recommended.

### 2.4.2 Installation Stress Analysis

Previous works have shown that a high level of stress is induced at locations of very tight curvature, high tension and high hydrostatic head (deepest point) (Huey, et al., 1995). Proper stress analysis is necessary to eliminate such conditions (From past researches up to date, in respect of HDD pipeline installation, it has been found that highest stress is felt at locations of very tight curvature, high tension (close to the rig side) and high hydrostatic head (deepest point). Proper stress analysis is necessary to eliminate such conditions stated above. PRCI (1995) adopted a method recommended by API RP 2A-WSD for the analysis.

#### 2.4.2.1 Actual stresses

- **Tensile Stress**

$$f_t = T/A \quad (2.11)$$

Where
T= Tension at the point of interest, kg or lbs
A= cross sectional area of pipe wall, inch

- **Bending stress**

$$f_b = (E \times D)/(24 \times R) \quad (2.12)$$

- **Hoop stress**

$$f_h = (\Delta p \times D)/(2 \times t) \quad (2.13)$$

Where
t= pipe wall thickness, inch or mm
Δp= difference between hydrostatic pressure exerted by the drilling mud around the pipe outside diameter and the pressure exerted by water, mud or air acting on the inside of the pipe, at the depth of point interest. (psi or Pa).
External mud pressure= mud weight (ppg) x depth (ft)/19.25

#### 2.4.2.2 Allowable Stresses

- **Tension**

$$F_t = 0.9 \times SMYS \quad (2.14)$$

Where
SMYS= Specified Minimum Yield Strength

- **Bending**

$$F_b = 0.75 \times SMYS \quad (2.15)$$

for $D/t \leq 1500000/SMYS$

$$F_b = [0.84 - \{1.74 \times D/(E \times t)\}] \times SMYS \quad (2.16)$$

for $1500000/SMYS < D/t \leq 3000000/SMYS$

$$F_b = [0.72 - \{0.58 \times SMYS \times D/(E \times t)\}] \times SMYS \quad (2.17)$$

for $3000000/SMYS < D/t \leq 300000$

- **Hoop Buckling Stress**

$f_h < F_{hc}/1.5$
where
$F_{hc}$= critical hoop buckling stress. It is a function of$F_{he}$, elastic hoop buckling stress

$$F_{he} = 0.88 \times E \times (t/D)^2 \quad (2.18)$$

(for long unstiffened cylinder)

$$F_{hc} = F_{he} \quad (2.19)$$

(for$F_{he}$Ij 0.55 x SMYS)

For inelastic hoop buckling,
$F_{hc}$= 0.45 x SMYS + 0.18 x $F_{he}$ (2.20)
(for 0.55 x SMYS <$F_{he}$ ≤ 1.6 x SMYS)
$F_{hc}$= 1.31 x SMYS/[1.15 + (SMYS/$F_{he}$)] (2.21)
(for 1.6 x SMYS <$F_{he}$≤ 6.2 x SMYS)
$F_{hc}$= SMYS (2.22)
(for$F_{he}$>6.2 x SMYS)

### 2.4.3 Load Checks

The unit check for combined stresses resulting from tensile and bending is given as;
$f_t/(0.9 \text{ x SMYS}) + f_b/F_b \leq 1.0$
The unit check for complete interaction of tensile, bending and external hoop stresses is given as;
$A^2 + B^2 + 2\nu \text{ x } [A] \text{ x } B \leq 1$
Where
A= ($f_t$ + $f_b$ – 0.5 x $f_h$) x 1.25/SMYS (2.23)

B= 1.5 x $f_h/F_{hc}$ (2.24)

ν= Poisson's ratio (0.3 for steel)

## 2.5 Case 2: Installation Loads and Stresses

The method adopted in Case 2 is the so-called Land and Marine (L&M) method, which holds that during a conventional HDD installation, the pipeline is subjected to the following loads and stresses at the pull-back stage:

- Tensile stresses resulting from the pull force
- Bending stresses resulting from the pipeline negotiating the curve of the borehole
- External hydrostatic pressure exerted on the pipeline by bentonite-based drilling mud, although omitted from L&M analysis

The method considers all the above installation stresses to be acting simultaneously in order to determine the worst case scenario. In the calculation, vertical radius of curvature is introduced to ensure better accuracy of results. The pipeline is assumed under a condition that the pulling force of the drill rig has been exerted on it. The situation of localized compressive stresses resulting in local buckling is also examined.
The following assumptions are used to assess the stresses induced when the pipeline is on the supports (conveyor rollers) and being pulled down hole;

- The entire pipeline rests on rollers spaced 12 meters from each other
- The pipeline takes all the load

Conveyor rollers used reduces the friction during installation, thereby reducing the required pull force to move the pipeline on conveyors. Friction factor on conveyors is 0.1. Friction factor for pipeline and drill pipe submerged in drilling fluid is 1.0 (assumed conservative).
Another assumption made is that the maximum anticipated pull force occurs at the start of the pipe pull. This assumption depends on the weight of pipe being pulled.

### 2.5.1 Pulling Load Calculation

The three conditions used for the pull-back load calculation are;

- Pipeline on conveyor – Pipeweights in air x Length of pipeline on conveyor x coefficient of friction of pipe on conveyors
- Weight of drill pipe down hole – Submerged weight of drill pipe filled with and surrounded by drilling fluid x coefficient of friction of drill pipe down hole.
- Pipeline down hole – Pipeweights submerged x length of pipeline submerged x coefficient of friction of pipe down hole.

The pulling load equation is given as;
$$P_1(x) = |W_{po}| \times (L - x) \times \mu_c + |W_{p1}| \times x \times \mu_s + |W_{d1}| \times (L_{drill} - x) \times \mu_s + \alpha \times W_h \quad (3.25)$$
Where
$P_1(x)$ = Maximum anticipated pulling load, ton
$W_{po}$= Weight of pipeline empty, in air, kg/m
L= Length of pipeline, m
x= Successive distance as the pipeline is pulled down hole
$\mu_c$= Friction coefficient for pipeline on conveyors
$\mu_s$= Friction coefficient for pipeline down hole
$W_{p1}$= Weight of empty pipeline submerged in drilling mud, kg/m
$W_{d1}$= Weight of drill pipe submerged and filled with drilling mud, kg/m
$L_{drill}$= Length of drill string, m
α= Ratio of steel weight in drilling fluid to weight in air
$W_h$= Weight of pulling head, kg
$$W_{po} = A_p \times \rho_{steel} \quad (2.26)$$
$$W_{p1} = W_{po} - (A_o \times \rho_{df}) \quad (2.27)$$
$$W_{d1} = W_{do} + (A_{id} \times \rho_{df} - A_{ed} \times \rho_{df}) \quad (2.28)$$
$$\alpha = \frac{\rho_{steel} - \rho_{df}}{\rho_{steel}} \quad (2.29)$$
Where
$A_p$= Cross sectional area of pipeline, $m^2$ or $mm^2$
$\rho_{steel}$ = Density of steel, $kg/m^3$
$A_o$= Outer area of pipeline, $m^2$
$\rho_{df}$= Density of drilling mud, $kg/m^3$
$W_{do}$= Drill pipe weight in air, $kg/m^3$
$A_{id}$= Internal area of drill pipe, $m^2$

$A_{ed}$= External area of drill pipe, $m^2$

### 2.5.2 Installation Stress Analysis

#### 2.5.2.1 Calculation of Stresses due to Spanning Rollers

$$M_e = \frac{W_{po} \times Ls^2}{8} \quad (2.30)$$

$$\sigma_{bs} = \frac{M_e \times D_o}{2 \times I_p} \quad (2.31)$$

$$\sigma_{bs\%} = \frac{\sigma_{bs}}{SMYS} \quad (2.32)$$

$$I_p = \frac{\pi(D_o{}^4 - D_i{}^4)}{64} \quad (2.33)$$

Where
$M_e$= Bending moment due to empty pipe spanning rollers, kNm
$\sigma_{bs}$= Bending stress induced in pipeline from spanning rollers, $N/m^2$
$\sigma_{bs\%}$= Bending stress as percentage of yield stress
Ls= Spacing of rollers, m
$I_p$= second moment of area of pipeline, $m^4$
$D_o$= Outer diameter of pipe, mm
$D_i$= Internal diameter of pipe, mm

#### 2.5.2.2 Calculation of Longitudinal Stresses due to Pipe Pull

Longitudinal stress in pipeline due to maximum pull force is given as;

$$\sigma_L = \frac{P_f}{A_p} \quad (2.34)$$

Where
$P_f$= Maximum pull force required to launch the pipeline, tonf
$\sigma_L$= Longitudinal stress in pipeline, $N/m^2$
$A_p$= Cross sectional area of pipeline
Longitudinal stress as a percentage of yield stress is;

$$\sigma_{L\%} = \frac{\sigma_L}{SMYS} \quad (2.35)$$

Condition for acceptance;
$\sigma_L + \sigma_{bs} < (SMYS)$

#### 2.5.2.3 Calculation of Tensile Stress

The tensile stress induced on the pipeline due to maximum pull capacity of the rig is;

$$\sigma_t = \frac{P}{A_p} \quad (2.36)$$

Where
$\sigma_t$= Tensile stress on pipeline ($N/m^2$)
P= Maximum available pull capacity of rig
Tensile stress as percentage of yield stress is;

$$\sigma_{t\%} = \frac{\sigma_t}{SMYS} \quad (2.37)$$

Allowable maximum pull force is given as;

$$P_{all} = f_d(SMYS \times A_p) \quad (2.38)$$

Where
$P_{all}$= Allowable maximum pull force, tonf
$f_d$= Design factor

#### 2.5.2.4 Curvature Stress on Pipeline

Pipe curvature stress is experienced when it is placed in the designated radius of curvature. Horizontal displacement of the pipeline is considered negligible, considering stress due to vertical radius of curvature as;

$$\sigma_{vr} = \frac{E \times D_o}{R_v} \quad (2.39)$$

Where
$\sigma_{vr}$= Vertical Curvature stress, $N/m^2$
E= Modulus of elasticity, MPa
$R_v$= Vertical radius of curvature, m
Bending stress as percentage of yield stress is;

$$\sigma_{vr\%} = \frac{\sigma_{vr}}{SMYS} \quad (2.40)$$

Combined effect tensile and bending stresses as percentage of pipe yield stress;

$$\sigma_{c\%} = \frac{\sigma_L + \sigma_{vr}}{SMYS} \quad (2.41)$$

#### 2.5.2.5 Local Buckling

The characteristic bending moment required to cause buckling when bending moments are acting alone is calculated as:

$$M_p = (D_o - t)^2 \times t \times SMYS \quad (2.42)$$

$$M_c = M_p\left(1 - 0.0024 \times \frac{D_o}{t}\right) \quad (2.43)$$

$$M_b = \frac{E \times I_p}{R_v} \quad (2.44)$$

Where
$M_p$=Full plastic moment capacity, kNm
$M_c$= Characteristic bending moment, kNm
$M_b$=Actual bending moment generated by minimum radius of curvature
Condition for acceptance; $M_b \leq M_c$

## III. RESULTS AND DISCUSSION

After analysis of the pull-back loads and stresses experienced by the pipeline in the case study, results were obtained based on the two methods analyzed which are now presented and discussed.

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### 3.1 Data Presentation

Consistent with the aim and objectives of the study, based on the problem statement in the previous chapter, design and analysis of pull-back loads and stresses on 24" (609.6mm) x 681.44m pipeline installed by method of HDD was conducted. The aim of the analysis is to predict the safe maximum pulling load and maximum stresses permissible for the pipeline, in order to ensure that the integrity of the pipeline is not compromised, and also to ensure that the installation process is not abandoned due to stuck pipeline down hole. Another reason for the analysis is to enable HDD pipeline installers to determine the appropriate size of drilling rig to deploy. A detailed presentation of the results is stated as follows.

### 3.2 Pull-back loads Calculations Analysis

#### 3.2.1 Mud Density Variation

Drilling mud density is one of the very important parameters in HDD pipeline installation that is capable of changing the pull-back force values appreciably. Just to reiterate on the previous facts established about the design philosophy of the two methods; PRCI method assumes that from the start of the pull, tension, T, is zero ($T_o = 0$), and that the maximum pull force (total pull force) is experienced at the end of the pulling process (at the exit towards the rig side). While L&M method assumes that the maximum pull (tension) is experienced at the start of the pull and progressively decreases as the pipeline is pulled out of the borehole (depending also on the weight of the pipe).Figures 3.1 and 3.2show the results obtained after performing the analyses with a mud density of 1100kg/m$^3$.

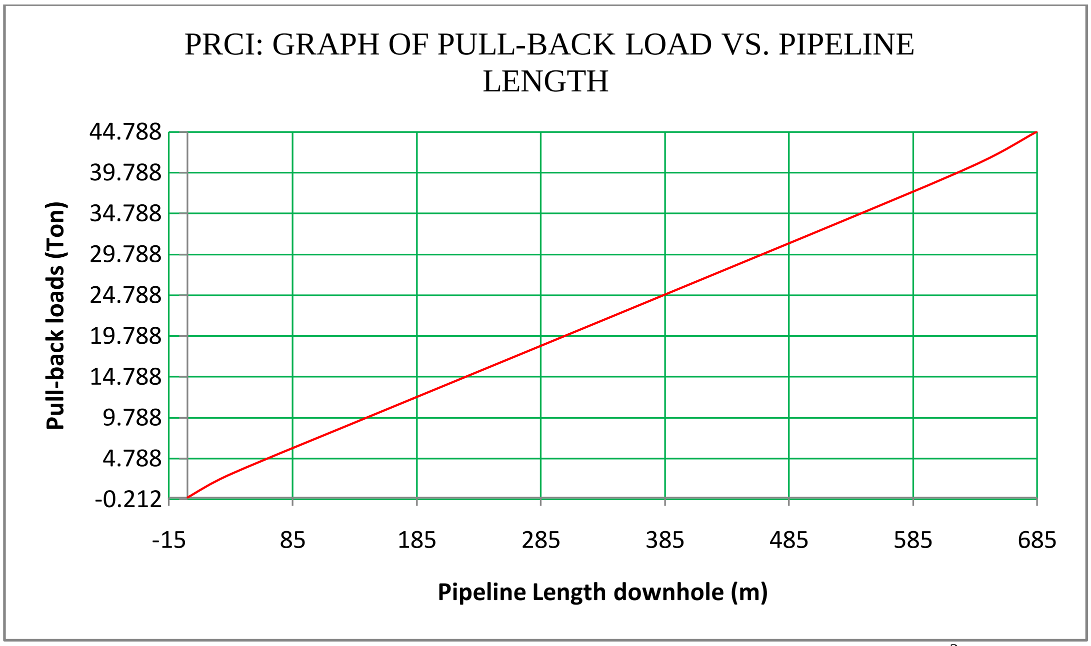


Fig. 3.1 PRCI Graph of Pull-back loads against Pipeline Length – 1100kg/m$^3$

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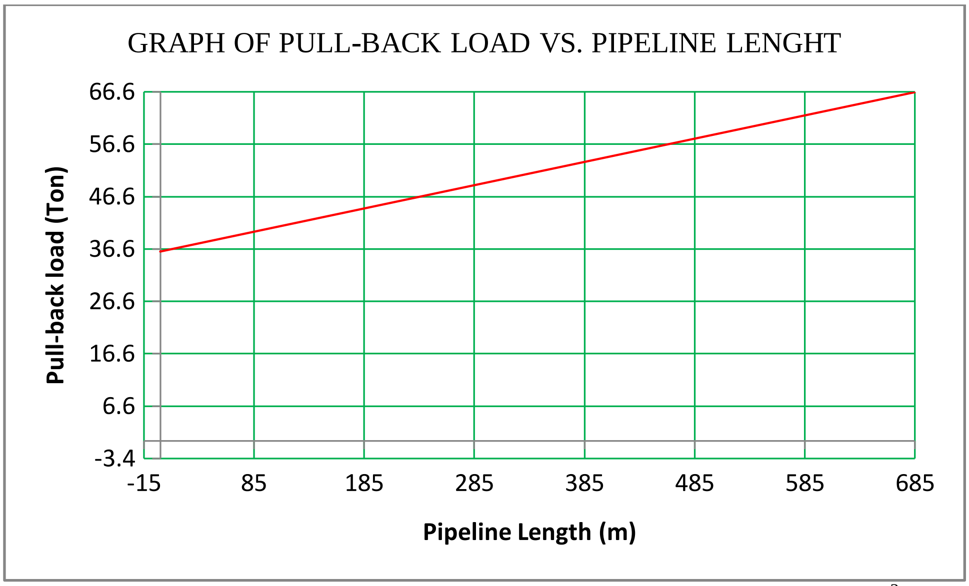


Fig. 3.2 L&M Graph of Pull-back loads against Pipeline Length – 1100kg/m$^3$

In the PRCI method, maintaining the drilling fluid at 1100kg/m$^3$ generated a pull-back force of 44.788 tons at the exit point (rig side) and 0ton at the beginning, while for L&M, it produced a pull-back force of 66.6tons at the end point (exit) and 36.13 tons at the starting point (entry). The graphs above for the two methods explain the variation. Figures 3.3 and 3.4 show the results when mud density is increased.

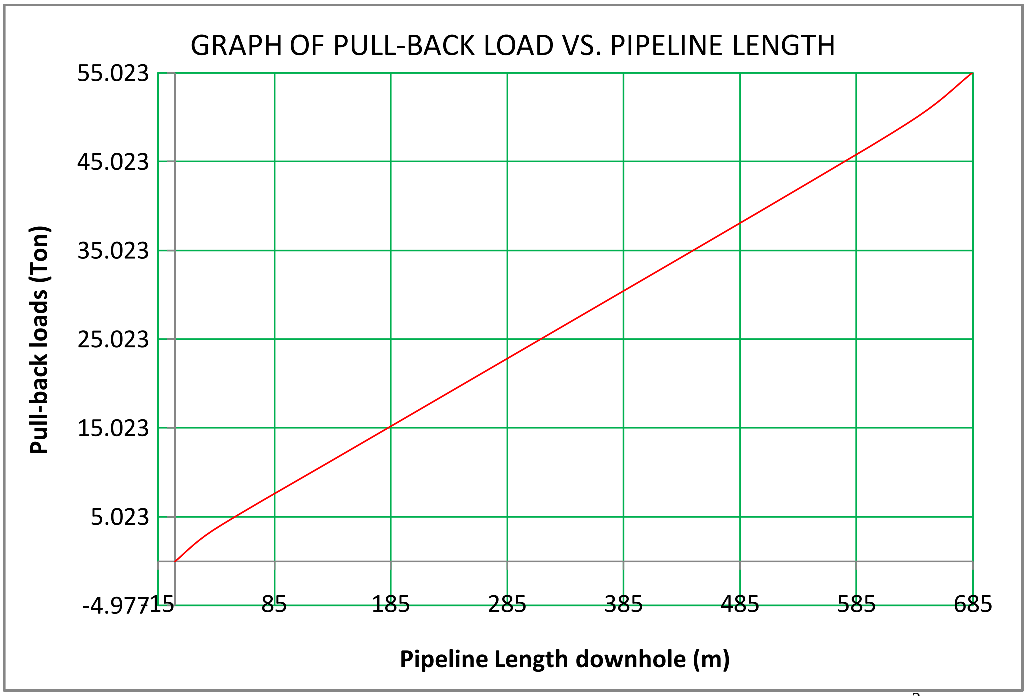


Fig. 3.3 PRCI Graph of Pull-back load against Pipeline Length – 1250kg/m$^3$

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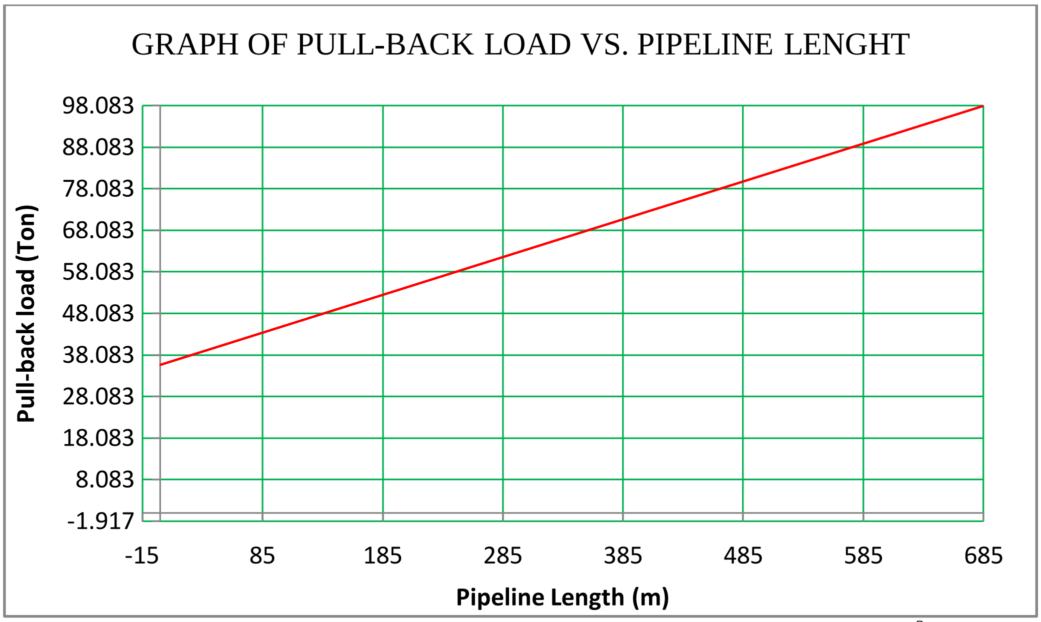


Fig. 3.4 L&M Graph of Pull-back load against Pipeline Length- 1250kg/m$^3$

On increasing the drilling fluid density to 1250kg/m$^3$, the PRCI method produced a pull-back force of 55.023 tons at the end point and 0ton at the start, while L&M method generated 98.1tons at the end point and 35.739 tons at the start point. Figures 3.5 and 3.6 illustrate the results obtained when drilling fluid is further increased to a much higher value

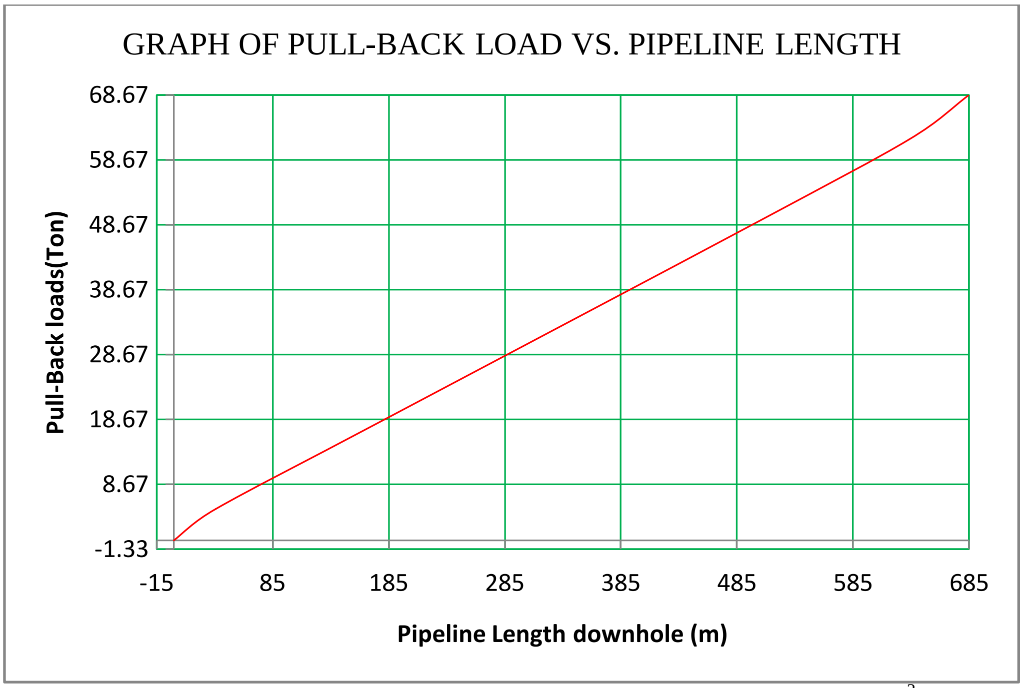


Fig.3.5 PRCI Graph of Pull-back load against Pipeline Length – 1450kg/m$^3$

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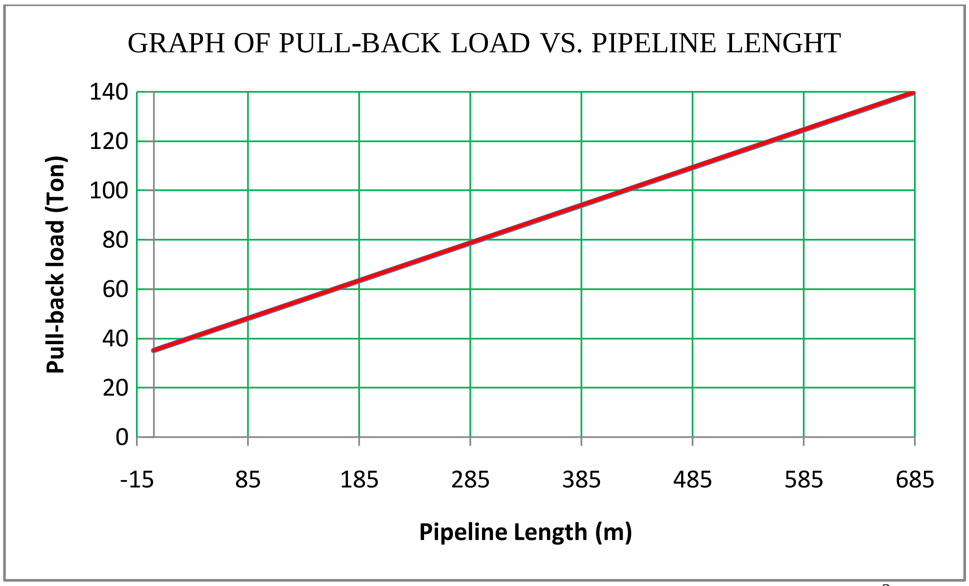


Fig.3.6 L&M Graph of Pull-back load against Pipeline Length – 1450kg/m$^3$

On further increasing the mud density to 1450kg/m$^3$, PRCI method produced 68.67tons at the end point and 0ton at the starting point, while L&M method produced 140tons at the end point and 35.218 tons at the start point.

From these results, it can be deduced that, increasing the drilling fluid density increases the pull-back force for both methods. The observable difference between the two methods is that; while the maximum pull force at the start decreased with an increase in mud density and increased at the end (for L&M), minimum pull force at the start increased with an increase in mud density from zero to maximum (for PRCI).

It is worthy of note that series of iterations were performed on the curved sections in PRCI methods in order to accurately predict the loads generated by the curved sections. The L&M method did not consider that as part of their design philosophy.

#### 3.2.2 Variation of Fluid Drag Coefficient and Friction Coefficient

Other very important parameters that alter pull-back loads results are fluid drag and friction coefficient down hole. A recommended value of fluid drag coefficient, 345 Pa, by NEN 3650 (NEN, 1999) was used in PRCI method, and it generated a very high pull-back force which appeared to be too conservative. But when 172 Pa was used as recommended by PRCI (2008), it produced a value almost half of that produced by 345 Pa. Therefore fluid drag coefficient of 172 Pa was used for the computation in PRCI method. L&M assumed friction coefficient (Drag coefficient) of 1.0 of pipeline down hole was compared with that of 0.8. Friction coefficient of 1.0 produced a value higher than that produced by 0.8 friction coefficient. This is so because they assumed a worst case scenario by using 1.0 as the friction coefficient.

### 3.3 Stress Calculations Analysis

Tables 3.1 and 3.2, and Figures 3.7 and 3.8 shown below illustrate the effect of mud density and Pull-back loads on Tensile Stress of the Pipeline during installation.

#### 3.3.1 Effect of Pull-back Load on Pipeline Tensile stress

Table 3.1 PRCI: Effect of Pull load on Tensile Stress

| Mud Density(kg/m$^3$) | mud density (ppg) | Pull-back load(Ton) | Tensile Stress (Mpa) |
|---|---|---|---|
| 1100 | 9.18 | 44.788 | 13.43 |
| 1250 | 10.432 | 55.023 | 16.44 |
| 1450 | 12.1 | 68.67 | 20.45 |

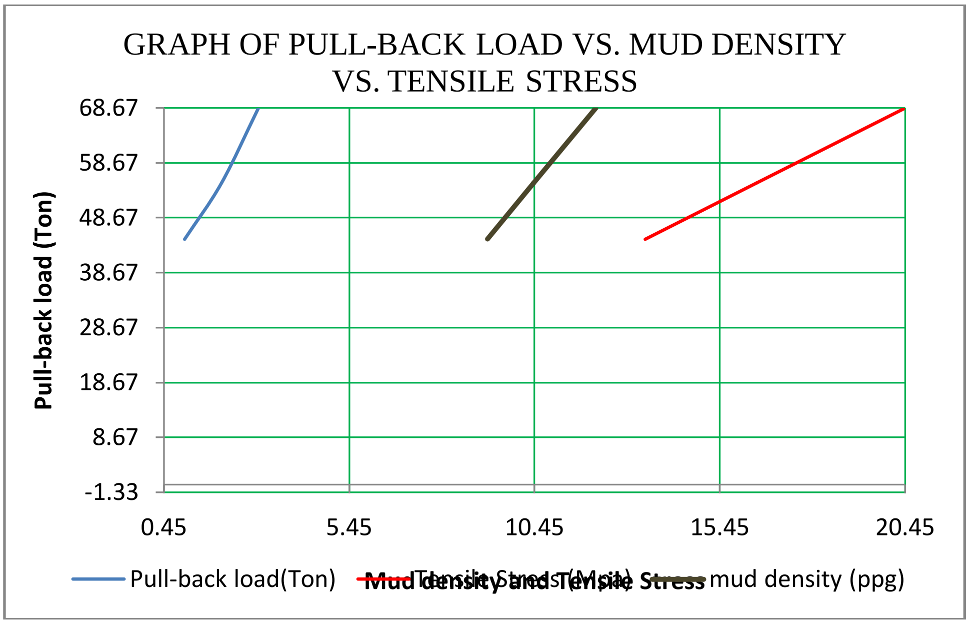


Fig. 3.7 PRCI Graph of pull-back load vs. mud density and tensile stress

Table 3.2 L&M: Effect of pull-back load on tensile stress

| mud density(ppg) | max. Pull-back load(Ton) | Tensile stress(Mpa) |
|---|---|---|
| 9.18 | 66.6 | 22 |
| 10.432 | 98.083 | 32 |
| 12.1 | 140 | 46 |

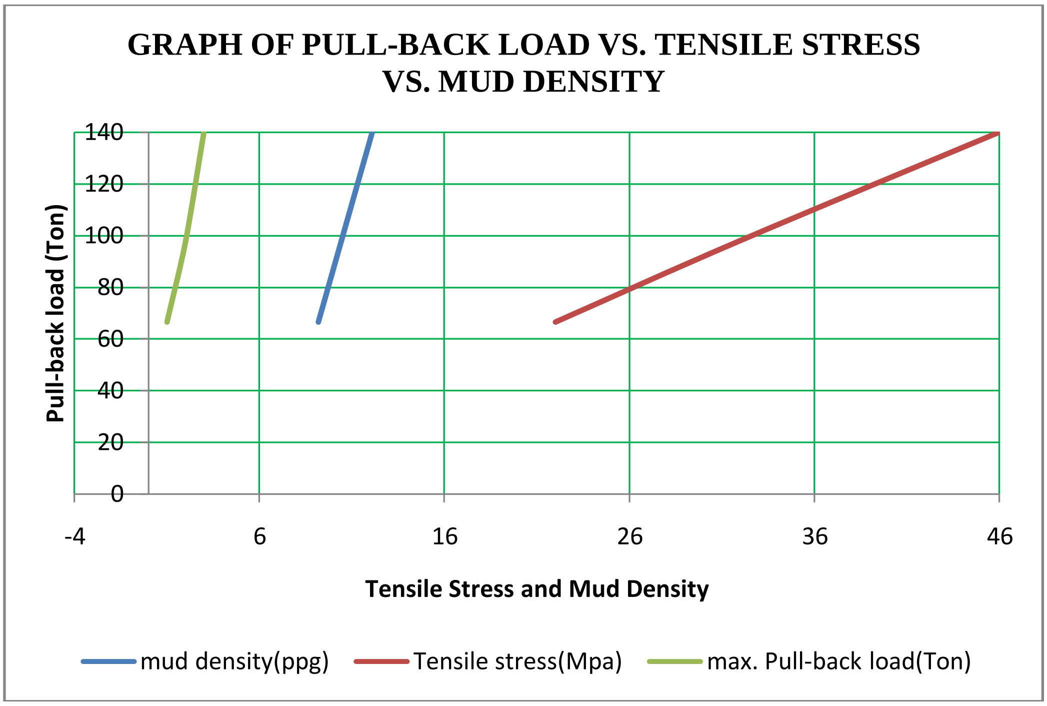


Fig. 3.8 L&M Graph of pull-back loads vs. mud density and tensile stress

From the tables and graphs shown above, it can be noticed that increased mud density increased pull-back loads which in turn increased the tensile stresses induced in the pipeline during installation. It can also be observed that the L&M method produced a higher tensile stresses as a result of higher Pull-back loads.

### 3.3.2 Bending and Buckling Stresses

Tables 3.3, 3.4 and 3.5 shown below illustrate the results obtained from the analyses of bending and buckling stresses.

Table 3.3 Bending Stress Calculation Values

| description | Bending Stress (MPa) | Maximum allowable bending stress (MPa) | Condition (Pass/Fail) |
|---|---|---|---|
| PRCI Values | 87.06 | 336 | PASS |
| | 87.06 | 336 | PASS |
| | 87.06 | 336 | PASS |
| L&M Engineering Values | 180 | 448 | PASS |
| | 180 | 448 | PASS |
| | 180 | 448 | PASS |

Table 3.4 Local Buckling of Pipeline (L&M)

| description | Full Plastic Moment Capacity, Mp (kNm) | Characteristic bending Moment, Mc (kNm) | Actual bending Moment, Mb (kNm) | Condition: Mb <Mc |
|---|---|---|---|---|
| L&M Engineering | 2511 | 2280 | 387 | ACCEPTABLE |

Table 3.5 External Hoop Stress (PRCI)

| Description | Hoop stress, $\sigma_{hoopE}$(MPa) | Maximum allowable hoop stress, $\sigma_{hoopEall}$ (MPa) | Condition: $\sigma_{hoopE} < \sigma_{hoopEall}$ |
|---|---|---|---|
| PRCI | 2.07 | 79.8 | PASS |
| | 2.35 | 79.8 | PASS |
| | 2.73 | 79.8 | PASS |

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Bending Stress values are higher for L&M method and impact more on the pipeline than that of PRCI method, though the stress values are within the acceptable limits. See appendices B and D for more details.

### 3.4 Comparison of Theoretical results with Actual Field results.

Figures 3.9 and 3.10, and table 3.6 shown below relate the theoretical analysis with the actual results obtained.

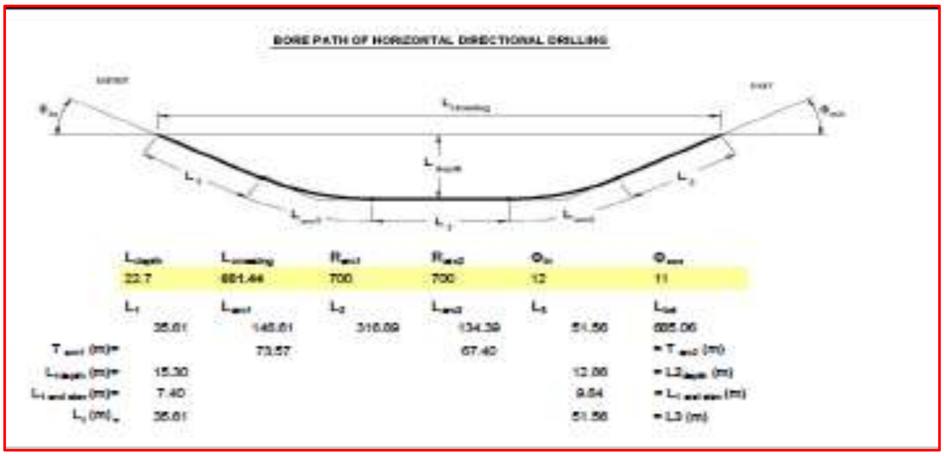


Fig.3.9 Detailed Drill Path Profile for the actual HDD Process

Table 3.6 Relationship between theoretical and actual results

| | Description | Theoretical Results for mud density of 1450kg/$m^3$ | Actual Field Results for mud density of 1395 kg/$m^3$ |
|---|---|---|---|
| PRCI Method | Pull-back load | 68.67 ton | 74.1 ton |
| | Tensile Stress | 20.45 MPa | 25MPa |
| | Max. allowable Tensile Stress | 403.2 Mpa | 403.2 Mpa |
| | Bending Stress | 87.06 Mpa | 90.13 Mpa |
| | Max. allowable Bending Stress | 336.119 Mpa | 336 Mpa |
| | Critical Hoop Buckling Stress | 448 Mpa | 448 Mpa |
| L&M Method | Pull-back load | 140 ton | 74.1 ton |
| | Tensile Stress | 48 MPa | 25MPa |
| | Max. allowable Tensile Stress | 403.2 Mpa | 403.2 Mpa |
| | Bending Stress | 180 Mpa | 90.13 Mpa |
| | Max. allowable Bending Stress | 336.119 Mpa | 336 Mpa |

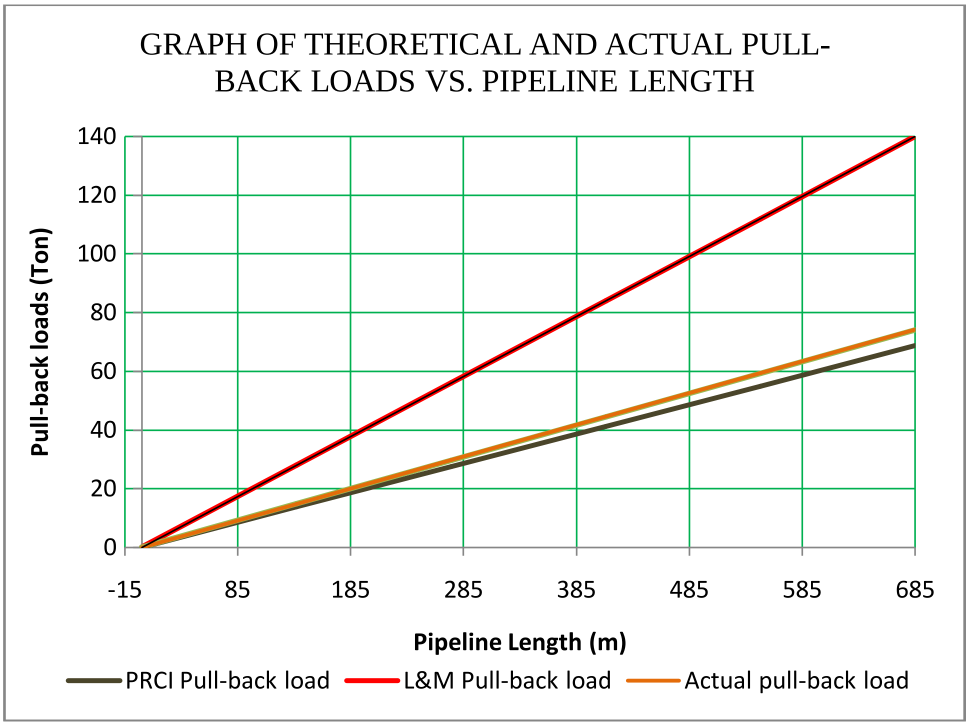


Fig 3.10 Graph of Theoretical Versus Actual Pull-back loads

**3.5 Discussion of Findings**

From the analysis of the pull-back loads and stresses of a typical 24" (609.6mm) x 681.44 m x 15.9 mm wall thickness pipeline installed by HDD, the following have been found.

The L&M method did not take into account entry and exit angles because it assumed that the effect on the entire installation is negligible. It considered the effect of drilling pipe in the pull-back process. The method assumptions consider the worst case scenario. The maximum values of pull-back loads obtained using this method are 66.6 ton with a mud density of 1100kg/m$^3$ and 140 ton with mud density of 1450kg/m$^3$.

PRCI method considered the inlet and exit angles with the assumption that they have significant impact on the entire installation process. It did not consider the weight of drill pipe because it does not act on the pull-back section. It assumed values that could cater for the worst case scenario, and the maximum pull-back force obtained is 68.67 ton with a mud density of 1450kg/m$^3$.

It has also been found that increasing the mud density increased the pull-back loads which automatically increase the tensile stress on the pipe material. Reducing the drag coefficients for both methods reduced the pull-back loads.

All the stress conditions for which the pipeline must withstand during installation have been checked and all passed the test. Stress values for both methods are not the same due to their design philosophy.

From the analysis, the L&M method is very straight forward but the PRCI method is quite difficult especially at the curved sections where iterations will have to be carried out to get the accurate tension at that point. Because of this, most designers who use the method apply factor of safety of 2.

Thiswork has now developed a Design Template using MATHCAD® software where all necessary parameters can be imputed to generate a pull-back force that is closer to the actual pull-back load obtained in the field. This Template has now eliminated the over conservative factor of 2 in design to between 1.15 and 1.25. The actual field result obtained is 74.1 ton with a mud density of 1395kg/m$^3$ while the theoretical values are 68.67 ton (1450kg/m$^3$) for PRCI and 140 ton (1450kg/m$^3$) for L&M. Multiplying the theoretical value of 68.67 ton with a safety factor of 1.25 yields 85.8 tonwhich is cheaper (less conservative) compared to that obtained with a safety factor of 2. The theoretical value of 140 ton is already high so should not be given a safety margin, except 66.6 ton with a mud density of 1100kg/m$^3$ is considered for use.

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# IV. CONCLUSIONS AND RECOMMENDATIONS

## 4.1 Conclusion

After performing analysis of pull-back loads and stresses on the case study pipeline stalled, the following conclusions are drawn:

Safe pull-back loads have been predicted and compared with actual field result. A reduced factor of safety ranging from 1.15 to 1.25 has been obtained.

Permissible stresses for the pipeline during installation have been determined and checked to be within acceptance criteria in accordance with ASME B31.8; maximum allowable tensile stress = 0.9 x SMYS of the pipe material.

Local buckling resulting from hoop stress has also been determined and checked to be within acceptance criteria in accordance with ASME B31.8; maximum allowable hoop stress = 67% of critical hoop buckling stress.

Mud density and fluid drag coefficient are very important factors that can increase or decrease the tension force in the pipeline, hence the need to design an optimal mud composition in an HDD Project.

A very high tension force has a significant effect on the pipe stress.

Bend radius also has an effect on the pipe stress. The smaller the bend radius the high the pipe stresses and vice versa.

## 4.2 Recommendations

From the analyses carried out, it is recommended that:

- Proper site/subsurface investigations should be conducted prior to commencement of an HDD Project. It would help to know the nature of the formation and the specification of drilling equipment to deploy.
- The methods used for the analyses are of sound engineering judgment, and are therefore recommended for use. But for a less conservative design, use PRCI's, and for more conservative design, use L&M's.
- As earlier stated, bend radius has a significant effect on pipe bending stress, and as such, a bend radius of 1200 times the nominal diameter is recommended.
- Even though site conditions can change some chosen parameters, it is recommended that extreme values be used to calculate for the worst case scenario.
- Experienced installation companies and Design Engineers should be consulted during HDD bidding.
- Pull-back loads should be accurately predicted to serve as a guide in HDD rig selection.

## 4.3 Contributions to Knowledge

This study has contributed to knowledge in the following aspects:

- Some design templates used by some HDD practitioners generate values that would require the application of a safety factor of 2, especially for PRCI method. The Design Template developed in this study has proved capable of generating values that would require a safety factor ranging from 1.15 to 1.25. It is capable of giving a closer prediction with the actual value.
- The pull-back loads predicted would serve as a guide when making selection for HDD rig, since using a large rig for small installation would induce much tensile stress on the pull section, and using a small rig for large installation could have the pipeline stuck down hole.
- The study has been able to identify some gaps between the two methods analyzed in this study.

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