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Analyses of Pipelines for Deep Horizontal Directional Drilling Installation

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Abstract This study examines the generic forces responsible for failure in pipelines installed by horizontal directional drilling (HDD), and proposes limiting load and stress criteria in order to prevent collapse, buckling or shear during installation and operation. Design equations from relevant codes and procedures were solved and integrated to create a common platform for analyzing installation loads, collapse and buckling forces in HDD pipelines. A comprehensive user friendly installation analysis tool which allows for multiple design settings, including buoyancy control has been developed in Microsoft Excel® platform. A pipeline with 1km HDD river-crossing was simulated and analyzed using the design tool. The results were analyzed and compared with that of existing commercial tools for HDD design. Since the results meet all specified design criteria, within the stated assumptions, it was found safe to proceed with the installation of the case study with a pulling load of 1000kN, using a 100-ton (≈ $10x10^4$N) HDD rig without risk of failure. Finally, this work has therefore provided a tool for quick estimation of limiting load and stress criteria for deep buried pipeline installations in order to prevent failure during installation and operation of such pipelines.

Keywords: *horizontal directional drilling, deep buried pipelines, combined installation stress factor, ovality*

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1. Introduction

1.1. Background

Pipelines are major means of transportation of oil and gas, and hence considered as part of national critical infrastructure [1]. However in developing nations, oil and gas pipelines are regularly vandalized or tapped by thieves to siphon the transported products, with its attendant socio-economic, and environmental costs and challenges [2]. Consequently, due to the many risks associated with onshore pipeline operation, deep burial option for pipeline installation is currently gaining increasing consideration by various operating companies [3]. Hence, Horizontal Directional drilling (HDD) technology has found application in several river crossing pipeline projects around the world.

According to Allouche *et al*. [4], to underscore the growing market for HDD technology, whereas only 12 HDD units were manufactured in 1984, this number increased to 2,000 units in 1995. Carpenter [5] estimated that as at end of 2010, 32,135 units were in circulation globally.

In Nigeria, though HDD pipeline installation technique is relatively new, there are remarkable achievements in the deployment of the technology. The Pan Ocean Energy Corporation‘s Amukpe-Escravos 508mm (20 inch) crude oil pipeline project, installed at depths ranging from 5m to 45m over 67km, was the largest HDD project in Africa [6]. The depth reportedly peaked at 45m in the segment below a 3.49km river crossing of the pipeline. It was completed in February, 2014 by Fenog Nigeria Limited. Several pipeline asset owners are currently considering replacement of their ageing and critical export pipelines with deep buried pipelines [7]. A 128km South-South Gas Transmission pipeline by the Oando Group undertaken by OilServ with ϕ450mm size covering 24 River-Crossings was commissioned in 2011-2013. Another large HDD is the SPDC-EGGS Gas pipeline installed by Ennikkom which was ϕ1000mm size of 0.76km which was commissioned by SPDC in 2010. Other major land and River Crossing projects completed by HDD have been reported by Engineering Network [8], Fenog [9], Okwuosa [10].

However, the design and operation of these pipelines pose several challenges including installation loads and maintenance constraints. These challenges have necessitated review of existing standards and practices with a view to developing a template for the design against collapse of deep buried pipelines at depths ≥ 10 m.

1.2. Theoretical Framework

Segments of a typical deep buried pipeline undergoing installation loads and stresses were idealized and appropriate equations determined, under given assumptions. A logical sequence was adopted to formulate, analyze and predict the effect of the installation and operating forces on the pipeline structure which was accomplished in the following order:

- Various theories and equations governing the design and operation of pipelines against shear, collapse and buckling failures, as prescribed by PRCI [11], ASCE [12] and API [13] were determined.
- The solutions of these equations were made amenable to problem solving algorithms and numerical schemes, to allow for implementation in a computer environment.
- Installation loads, collapse pressure and buckling loads were used to simulate the installation design template developed which allows optimization of pipelines at various depths ≥ 10 m using varying conditions.
- The results thus obtained were compared with those of an existing deep buried pipeline and those of a commercial pipeline Toolbox.

The HDD process reportedly [14] starts with the: (1) drilling of the pilot hole, (2) reaming or expansion of the pilot hole to obtain a hole of about 1.5 times the size of the pipeline to be installed, and finally (3) the pullback operations.

1.3. Design Considerations

1.3.1. Drilled Hole Path

The drilled path hole must be properly designed to avoid obstacles and existing HDD installations. An irregular path poses danger to the installation because of induced stresses on the pipe due to constrictive bends or misalignments.

1.3.2. Penetration Angle

HDD penetration angles are generally designed between 8° and 20°. Most horizontal drilling rigs are designed to function best between 10° and 12° [15]. For large-diameter pipelines, entry angles may be < 8°. Exit angles should be from 5° (for large-diameter steel pipelines) to 12° [16].

1.3.3. Radius of Curvature

The radius of curvature typically used in HDD path design is 1,200 times pipe diameter [15]. This relationship (R=1200D) is derived from established practice for steel pipe rather than theoretical analysis because radius R < 1200D leads to increased bending stresses and pulling loads.

1.3.4. Depth of Cover

DCCA [16] recommends that a minimum of about 5m distance beneath the obstacle be maintained but for less favorable drilling conditions about 7.5m can be used.

1.3.5. Related Design Codes and Standards

Pipeline design for HDD installation is an iterative process that requires thorough evaluation and analysis. However, in this study, since there is no single comprehensive standard available, a combination of some existing standards and codes were utilized by harnessing their relevant design recommendations. Hence, three (3) analysis methods - PRCI [12], ASCE [13], and API [14] were identified with acceptable conformity.

PRCI method does not adequately model the earth pressure because pipe arching factor is not considered. The ASCE manual [13] considers the arching factor in developing equations for external pressure calculations. However, both methods failed to model pipe collapse. API [14] modeled pipeline collapse but neglects pulling loads. Hence, this study combines the various key design elements in other to estimate the buckling, collapse and installation forces and stresses on deep buried pipelines.

1.4. Design Criteria

These include: unity checks to determine if the pipeline will fail by combined tension, bending or shear - Combined Installation Stress Factor (CISF), Collapse and buckling criteria for predicting buckling of pipelines due to external pressure and / or bending. The buckling criterion also captures design against excessive ovality and buckling strain under pure bending.

The aim of the study was to develop an installation design template for evaluating loads and stresses on HDD pipelines, analyzing buckling forces and collapse pressure; and optimization based on ultimate pulling load, material grade and wall thickness, which is compared with a commercial PRCI Tool.

2. Methodology

2.1. Research Design

2.1.1. Input Data

This primarily involves pipeline and soil data such as: pipeline size, wall thickness, operating pressure and temperature, material grade, thermal coefficient, installation temperature, design factor, specified minimum yield strength of material, modulus of elasticity of material, Poisson ratio, temperature de-rating factor and depth of burial. Others are soil and drilling mud properties like soil friction factor, soil friction angle, soil density, fluid drag coefficient and mud density. These are important in determining the load and stress conditions and hence, the installation viability.

2.1.2. Processing

Input data processed to determine the generic forces and stresses during installation and operation, using well established mathematical and semi-empirical models from PRCI [12], ASCE [13], and API [14]. The PRCI Drill-Path Analysis Method was used to compute pulling loads during installation.

Other parameters necessary for load and stress processing include pipe cross-sectional area, steel cross-sectional area; weight of pipe, displaced and submerged mud weight, earth pressure, arching factor and design pressure.

2.1.3. Output Data

Output data include pulling loads at different (straight and curved) sections of the pipeline, and stresses (tensile, bending and hoop) as primary output. Allowable loads and stresses were estimated from the primary output based on established stress criteria to determine feasibility of installation based on project specification (input data).

2.2. Sources of Data

Primary data for the case study, a 610mm (24-inch) x 24.59mm x 20km crude oil pipeline to be installed, were obtained from an HDD Construction company in Nigeria. These comprised the pipeline design data, soil conditions and depth of burial.

Pipeline design data include: pipeline diameter – 610 mm (24in); wall thickness - 24.5872 mm; material - API 5L X52, Specified minimum yield strength – 359 MPa; Design Factor (Location Class 1 Div.2) – 0.72; Steel Density 7850 kg/m^3; Installation Temperature - 30^{o}C; operating temperature – 70^{o}C; Weld Joint Factor – 1 (seamless pipe); Temperature Derating Factor - 1 (Operating Temperature < 121^{o}C); Modulus of Elasticity - 207 GPa; Thermal Coefficients - 0.0000117/mm/°K; and Poisson ratio - 0.3 (steel). The input soil (mud) properties include: Soil Density - 1800 kg/m^3; Soil Friction angle - 30°, Soil Friction Factor - 0.3, Water Density - 1000 kg/m^3 , Mud Density - 1480 kg/m^3 , Mud Drag Coefficient - 0.3.

Secondary design data including evaluation constants, material and soil properties, mathematical and semi-empirical models were obtained from Manuals and Design Standards such as ASCE [13], ASME [18] and PRCI [12].

2.3. Method of Data Analysis

The PRCI (Drill-path Analysis), ASCE and API [14] Methods were used for data analysis. Computations were based on the design equations and other standards. The analysis was performed without the use of water for buoyancy control, though, the HDD design template developed in this study allows for multiple design and installation scenarios, including buoyancy control.

2.3.1. Simulation of the Case Study

To evaluate the performance of the design template developed the crude oil pipeline case study to be installed having a river crossing of about 1km with 20m depth of burial beneath the river bed was investigated. The specified entry and exit angles are 10°. Radius of curvature for the curved surface during installation is 1200D [m]. The soil is the typical alluvial soil with < 30% gravel composition by weight prevalent in the Niger-Delta. Drilling mud for the installation was bentonite- based drilling mud (Hydraul-EZ®) with the ability to stabilize bore, return cuttings and reduce friction between the bore wall and pipe. The objective was to estimate the pulling force required to carry out the installation, and hence determine the appropriate rig, the suitability of pipe size and material grade, and the general feasibility of the installation.

As a solution precursor, geometry parameters and relevant constants such as Pipe cross-sectional area (A_p), steel cross-sectional area *(*A_s*)*, earth Pressure (P_e), weight of pipe W_s, effective or submerged weight of pipe (W_{sub}), arching factor (κ), among others were estimated.

From ASME [18], the pipe internal cross-sectional area A_p and the steel cross-sectional area A_s are given by

$$A_p = \frac{\pi}{4}(D_o - 2t)^2 \tag{1}$$

$$A_s = \pi t(D_o - t). \tag{2}$$

Also the weight of the pipe in air per metre (W_p) is given by

$$W_p = A_s * \rho_s. \tag{3}$$

The Design Pressure is given by

$$P_d = \frac{2F * E * S * t}{D}. \tag{4}$$

The earth loads were computed using ASTM [19] method as:

$$P_e^{'} = \kappa \rho_s H. \tag{5}$$

The arching factor κ is calculated from;

$$\kappa = \frac{1 - \exp[-(2KH / B)\tan(\phi / 2)]}{(2KH / B)\tan(\phi / 2)}. \tag{6}$$

The earth Pressure coefficient is calculated as:

$$K = \tan^2(45 - \phi / 2) \tag{7}$$

and displaced mud weight as:

$$W_{disp-m} = A_p * \rho_m. \tag{8}$$

Submerged Pipe weight W_{sub} *becomes;*

$$W_{sub} = w_{disp-m} - W_p. \tag{9}$$

2.3.2. Installation Loads and Stresses

During HDD installation, a pipeline segment is subjected to tension, bending, and external pressure as it is pulled through a pre-reamed hole. The stresses and failure potential of the pipe are due to the interaction of these loads [12]. To determine whether a given pipe specification is adequate, HDD installation loads must first be estimated so that the resultant stresses can be calculated. The following loads were considered in the template development.

2.3.2.1. Tension

Tension on the pulled pipe section is primarily generated from: (a) frictional drag between the pipe and the wall of the hole, (b) fluidic drag from the drilling fluid surrounding the pipe and (c) effective submerged weight of the pipe [13].

The processed output include: Pipe internal cross-sectional area - 0.2467m^2 ,steel cross-sectional area - 0.0452m^2, Design pressure – 289.5933bar, weight of pipe in air – 354.7278kg/m, Earth pressure coefficient – 0.5774, Arching factor κ – 0.9998, Earth loads – 0.3599MPa, Displaced mud weight – 354.5959kg/m, Submerged pipe weight – 0.1309kg/m.

2.3.2.2. Bending

The pull section is subjected to elastic bending as it is forced to negotiate the bore curvature. For a pipe with welded or fused joints, this induces flexural stresses dependent upon the drilled radius of curvature. For steel pipe, the relatively rigid material resistance to bending also induces a normal bearing force against the bore wall [13].

2.3.2.3. External Pressure

External Pressure on the pulled pipe is due to four different forces [13].

- Hydrostatic pressure from the weight of the drilling fluid surrounding the pipe in the drilled annulus.
- Hydrokinetic pressure required to produce fluid flow from the reaming assembly through the annulus to the surface.
- Hydrokinetic Pressure produced by surge or plunger action while pulling the pipe into the reamed hole.
- Bearing Pressure of the pipe against the bore wall forcing the pipe to conform to the drilled path.

2.3.2.4. Impact of Live Loads

According to ASCE-American Lifeline Alliance Guidelines for the Design of Buried Steel Pipes [20], the impact of live loads depends on the depth of cover. It is negligible for lHS-20 loads (Cars and Truck Loads) when the earth cover exceeds 2.44m; E-80 loads (Rail and Aircraft Loads) when the earth cover exceeds 9.14m; The HDD pipeline design data shows that the depth of burial exceeds 10m and by implication, surface loads over the pipeline right of way have negligible effect.

2.3.3. Drill-Path Analysis

A typical HDD drill path profile consists of three straight sections (L_1, L_2, and L_3) and a curved section ($\frown L_1 = L_1'$ with radius of curvature R_1) separating L_1 from L_2, and a second curved section ($\frown L_2 = L_2'$ with radius of curvature R_2) separating L_2 from L_3. The straight sections are analyzed as in Figure 1.

For any straight section as shown in Figure 1,

$$T_2 = T_1 + |\ fric.| + F_D \pm W_{sub} * L \sin\theta\ . \qquad (10)$$

The ± term is negative (-) if T_2 tends down-hole, positive (+) if T_2 tends up-slope and zero (0) for $\theta = 0$.

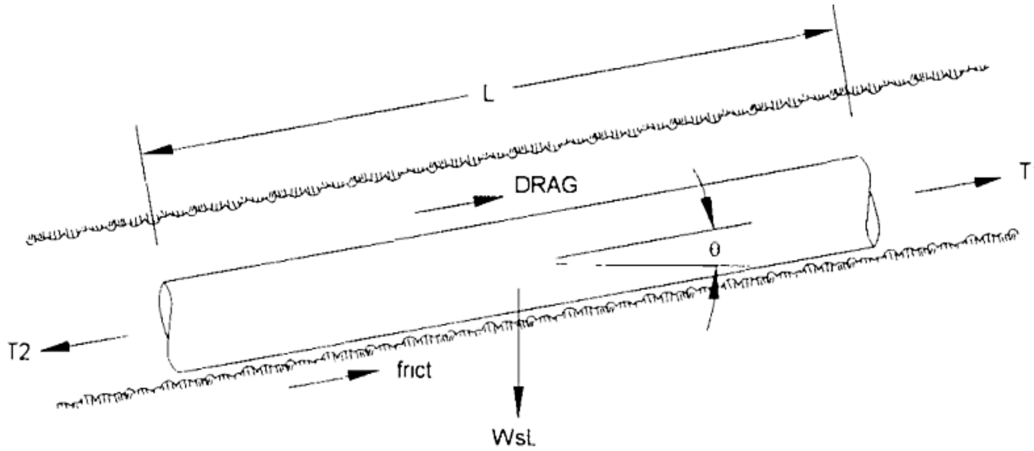

Figure 1. HDD Straight Section model [21]

$$Fric = W_{sub} * L * \cos\theta * \upsilon_{soil} \qquad (11)$$

$$F_D = DRAG = \pi D * L * \upsilon_{mud} \qquad (12)$$

υ_{soil} - average coefficient of friction between pipe and soil; recommended values between 0.21 - 0.30.

υ_{mud} - fluid drag coefficient for steel tube pulled through bentonite mud; recommended value 344.5Pa (0.05 psi) [12].

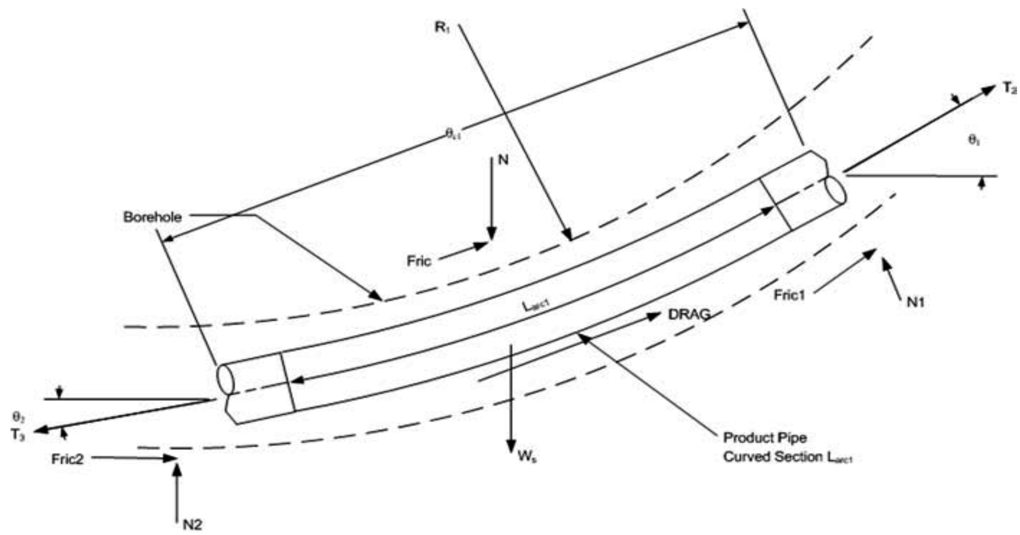

Figure 2. Curved Section of a typical HDD Pipeline [21]

The curved section is analyzed using Figure 2 for:

R_1- the radius of curvature between points 2 and 3;

θ_1- the angle from horizontal of T_2 at the right end section;

θ_2- the angle from horizontal of T_3 at the left end section;

$$\theta = (\theta_1 + \theta_2)/2. \quad \mathrm{L_{arc}} = (\mathrm{R} * \theta). \tag{13}$$

The values fric, $fric_1$, and $fric_2$ are the frictional forces at the center, right, and left section [4]. From Roark's solution for elastic beam, the following solutions are developed for the forces acting on the pipe curved section.

$$N = \frac{T_{est} * h - W_{sub} * \cos(\frac{\theta}{2}) * Y}{X}. \tag{14}$$

But,

$$h = R(1 - \cos\frac{\theta}{2}), \tag{15}$$

$$X = 3 * \frac{L_{arc}}{12} - (\frac{j}{2}) * \tanh\left[\frac{U}{2}\right] \tag{16}$$

$$Y = 18 * \left[\frac{L_{arc}}{12}\right]^2 - j^2 * \left[1 - (\cosh(\frac{U}{2}))^{-1}\right] \tag{17}$$

$$j = \left[E * \frac{I}{T_{est.}}\right]^{0.5}, \tag{18}$$

$$I = \pi * [D - t]^3 * \frac{t}{8} \; and \; U = \left[\frac{L_{arc}}{j}\right]. \tag{19}$$

L_{arc} could either be L_1' or L_2'.

$T_{est.}$ is the estimated pull force required to sufficiently pull the pipe through the hole section. By rule of thumb,

$$\left[\frac{T_2 + T_3}{2T_{est}} - 1\right] \le 0.1\left[\frac{T_2 + T_3}{2}\right]. \tag{20}$$

Equation (20) iteration continues until;

$$T_{est} \le 0.1(T_2 + T_3)/2. \tag{21}$$

For the curved section;

$$fric = | N \times \upsilon_{soil} |. \tag{22}$$

Total Force T_2 at end of L_1, becomes;

$$T_2 = T_1 + | \; fric. | + F_D \pm W_{sub} * L \sin\theta_1. \tag{23}$$

For all N values, the friction values are positive, acting in T_3 direction. Hence, the force at point 3 becomes;

$$\Delta T_3 = 2 * | \; fric | + F_D \pm W_{sub} * L_{arc} * \sin(\frac{\theta}{2}). \tag{24}$$

The total Pulling force at point 3 becomes $\Delta T_3 + T_2$.

$$T_3 = T_2 + 2 * | \; fric | + F_D \pm W_{sub} * L_1' * \sin(\frac{\theta_1}{2}) \tag{25}$$

$$L_2 = L_{crossing} - \begin{pmatrix} L_1 Cos\theta_1 + L_3 \cos\theta_2 \\ + R_1 \sin\theta_1 + R_2 \sin\theta_2 \end{pmatrix}. \tag{26}$$

Applying Eqs. (10) – (12) to the straight section (L_1) the following parameter values were obtained: L_1 – 51.1757m, θ_1 - 10°, fric – 9.8015kN, F_D = DRAG – 33.787kN, $W_{sub} * L * \sin\theta_1$ = -5.7609kN and total force T_2 (for T_1 = 0) – 49.3495kN.

Applying Eqs. (13) – (26) to the curved section (L_1') the following parameter values were obtained: L_1' – 731.529m, T_{est} – 50.0000kN, h – 2.7837m, X –4.5027m, Y – 358.104m^2, J – 89.4604m, I – 0.0019 m^4, U – 1.4272, N – 82.2732kN, fric - 24.682kN, F_D – 84.293kN, $W_{sub} * L_{arc} * \sin(\frac{\theta_1}{2})$ - 0.0146kN, and Total force T_3– 190.22kN.

Applying Eqs. (10) – (12) to the horizontal section (L_2) the following parameter values were obtained: L_2 – 645.1493m, θ_1 – 0°, fric – 125.4693kN, F_D – 425.938kN, $W_{sub} * L_2 * \sin\theta_1$ - 0kN (at θ_1 = 0°), and Total Force T_4 at end of L_2- 741.6274kN.

Applying Eqs. (13) – (26) to the curved section (L_2') the following parameter values were obtained: L_1' – 731.5200m, T_{est} – 175kN, h – 2.7837m, X – 4.5027m, Y – 358.1042m^2, J – 89.4608m, I – 0.0019m^4, U – 1.4272, N – 159.5514kN, fric–47.8654kN, F_D – 84.2927kN, $W_{sub} * L_{arc} * \sin(\frac{\theta_2}{2})$ - -7.2137kN, and Total force T_5 – 914.4373kN.

Applying Eqs. (10) – (12) to the straight section (L_3) the following parameter values were obtained: L_3 – 51.1757m, θ_2 – 10°, fric – 9.8015kN, F_D – 33.7871kN, $W_{sub} * L_3 * \sin\theta_1$ - -5.7609kN, and Total Force T_6 at end of L_3 – 952.265kN.

Therefore, total pull force required for the case study pipeline installation in the 1km river-crossing is 952.265kN without filling the line with water.

2.3.4. Installation Stresses

According to PRCI [12], the worst case stress condition for the pipe will be located at the point where the most serious combination of tensile, bending and/or hoop stresses occur simultaneously. In general, highest stresses occur at locations of tight radial bending, high tension, and high hydrostatic head.

2.3.4.1. Tensile Stress σ_t

The tensile stress is determined by Eq. (27) as,

$$\sigma_t = \frac{T}{A_s} \tag{27}$$

By API [22] standard, the maximum allowable tensile stress should be; $\sigma_t \le 0.9S$

2.3.4.2. Bending Stress σ_b

Bending stress due to pipe conforming to the drilled radius of curvature R is given by Eq.(28) [13].

$$\sigma_b = \frac{ED}{2R} \tag{28}$$

PRCI [12] design criteria for bending stress on HDD Pipeline during installation is as follows.

$$\sigma_B = 0.75S. \text{ For } D/t \le (1{,}500{,}000/\mathrm{S}) \tag{29}$$

$$\sigma_B = \left[0.84 - (1.74SD)/(Et)\right]S$$
For $1,500,000/S < D/t \leq 3,000,000/S$ (30)

$$\sigma_B = \left[0.72 - (0.58SD)/(Et)\right]S$$
For $3,000,000/S < D/t \leq 300,000$. (31)

2.3.4.3. Hoop or Circumferential Stress

Hoop stress due to external Pressure can be checked by the criteria for tubular members in offshore structures [22].

$$\sigma_h = (P_o * D)/(2t) \tag{32}$$

$$\sigma_{he} = 0.88E(t/D)^2. \tag{33}$$

For long unstiffened cylinders,

$$\sigma_{hc} = \sigma_{he} \text{ For } \sigma_{\text{he}} \leq 0.55\text{S} \tag{34}$$

$$\sigma_{hc} = 0.45S + 0.18\sigma_{he} \text{ for } 0.55\text{S} < \sigma_{\text{he}} \leq 1.6\text{S} \tag{35}$$

$$\sigma_{hc} = 1.31S/\left[1.15 + (S/\sigma_{he})\right] \text{ for } 1.6\text{S} < \sigma_{\text{he}} \leq 6.2\text{S} \tag{36}$$

$$\sigma_{hc} = S \text{ For } \sigma_{\text{he}} > 6.2\text{S}. \tag{37}$$

From Eq.(32) – (37), hoop stress from external pressure σ_h and critical hoop buckling stress σ_{hc} are limited by $\sigma_h \leq \sigma_{hc}/1.5$.

2.3.4.4. Collapse Pressure and Buckling

The criterion requires that the pipe selection provides a pipe of adequate strength to prevent collapse in case the external pressure exceeds the operating pressure of the pipeline. The collapse pressure of the pipeline shall exceed the net external pressure at every point on the pipeline as follows [14].

$$f_o P_c \geq (P_o - P_i) \tag{38}$$

for,
f_o = 0.7 for seamless or electric resistance welded (ERW) pipe; and
f_o = 0.6 for cold expanded pipe - double submerged arc welded (DSAW) pipes.

Eqs. (39) – (41) were used to estimate collapse pressure [14]:

$$P_c = \frac{P_y P_e}{\sqrt{P_y{}^2 + P_e{}^2}} \tag{39}$$

$$P_y = 2S\left(\frac{t}{D}\right) \tag{40}$$

$$P_y = 2E\frac{\left(\frac{t}{D}\right)^3}{(1-\nu^2)} \tag{41}$$

To prevent buckling due to combined bending and external Pressure Eqs, (42) – (46) must be satisfied.

$$\frac{\varepsilon}{\varepsilon_b} + \frac{(P_o - P_i)}{f_o P_c} \leq g(\delta) \tag{42}$$

$$\varepsilon_b = \left(\frac{t}{2D}\right) \tag{43}$$

Collapse reduction factor

$$g(\delta) = (1 + 20\delta)^{-1} \tag{44}$$

$$\delta = \text{ovality} = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}}. \tag{45}$$

To prevent buckling, bending strains:

$$\varepsilon \geq f_1 \varepsilon_1 \tag{46}$$

Where;
f_1- bending safety factor for installation bending strain plus external pressure, usually taken as 2.00; and
ε_1 - maximum bending strain usually taken as 0.15%.

2.3.4.5. Combined Installation Stresses

Combined stress analysis checks the axial tension and bending according to Eq. (47) limiting criterion [12].

$$\frac{\sigma_t}{0.9S} + \frac{\sigma_b}{\sigma_B} \leq 1. \tag{47}$$

The full interaction of axial tension, bending, and external pressure stresses should be limited by Eq. (48) criteria:

$$A^2 + \mathbf{B}^2 + 2\nu|A|B \leq 1 \tag{48}$$

where; $A = \left[(\sigma_t + \sigma_b - 0.5\sigma_h)1.25\right]/S$ (49)

$$B = 1.5\sigma_h/\sigma_{hc} \tag{50}$$

PRCI [12] notes that failure to satisfy the unity check (Eq. (48)) does not mean that the pipeline will necessarily fail by overstress or buckling. Rather, it indicates that the combined stress state places the design in a range where some specimens under similar stress-state have failed.

2.3.5. Operating Stresses

HDD pipelines are subjected to the same operating stresses as trenched pipelines with additional bending stresses. Longitudinal and hoop stresses will result from internal pressure and thermal expansion / contraction. Bending stresses due to HDD installation is checked in combination with other longitudinal and hoop stresses experienced in operation to compare with acceptable limits.

2.3.5.1. Internal Hoop Stress, σ_h

By ASME [18] hoop stress due to internal pressure becomes:

$$\sigma_{hi} = (P_i D)/(20t). \tag{51}$$

2.3.5.2. Thermal Stress, σ_e

Thermal stresses due to temperature difference between the soil and pipe given by:

$$\sigma_e = E\alpha\left(T_1 - T_2\right) \tag{52}$$

α =coefficient of thermal expansion for steel in mm./°K;

2.3.5.3. Combined Operating Stresses

Hoop, thermal, and bending stresses imposed on the pipe during operation are combined, to evaluate the risk of failure. This is accomplished by examining the maximum shear stress at selected elements on the pipe. Maximum shear stress is given by Eq. (53)

$$\sigma_v = (\sigma_c - \sigma_l)/2. \tag{53}$$

The criterion is that maximum shear Stress should not exceed 45% of the specified minimum yield strength [23].

The total longitudinal stress is the sum of the bending, thermal stresses, and the longitudinal component of circumferential (Hoop) stress which is determined as;

$$\sigma_l = \sigma_e + \sigma_b + (v\sigma_c). \tag{54}$$

This value should not exceed 90% of the Specified Minimum yield Strength. The total circumferential stress is the difference between the internal and external hoop stresses thus;

$$\sigma_c = \sigma_h - \sigma_{hi}. \tag{55}$$

3. Results and Discussion

3.1. Data Presentation

An MS-Excel® Installation design Template, Figure 3, developed to facilitate the simulation of multiple design and analysis with varying parameters. For the case study, a 610mm x 24.75mm x 20km pipeline with 1km HDD river-crossing, load and stress analyses were based on the template to ascertain the pipeline installation integrity.

3.1.1. Stress Calculations Results and Status Check

From the preceding discussions, the stresses associated with the installation of the case study, given the installation and operating conditions include:

- **Tensile stress Results:**

Tensile Stress, $\sigma_t = \dfrac{T}{A_s}$ - 21.0733 MPa; Allowable $\sigma_t = 0.9S$ - 323.1000 MPa; Status ($\sigma_t \le 0.9S$) – Satisfactory.

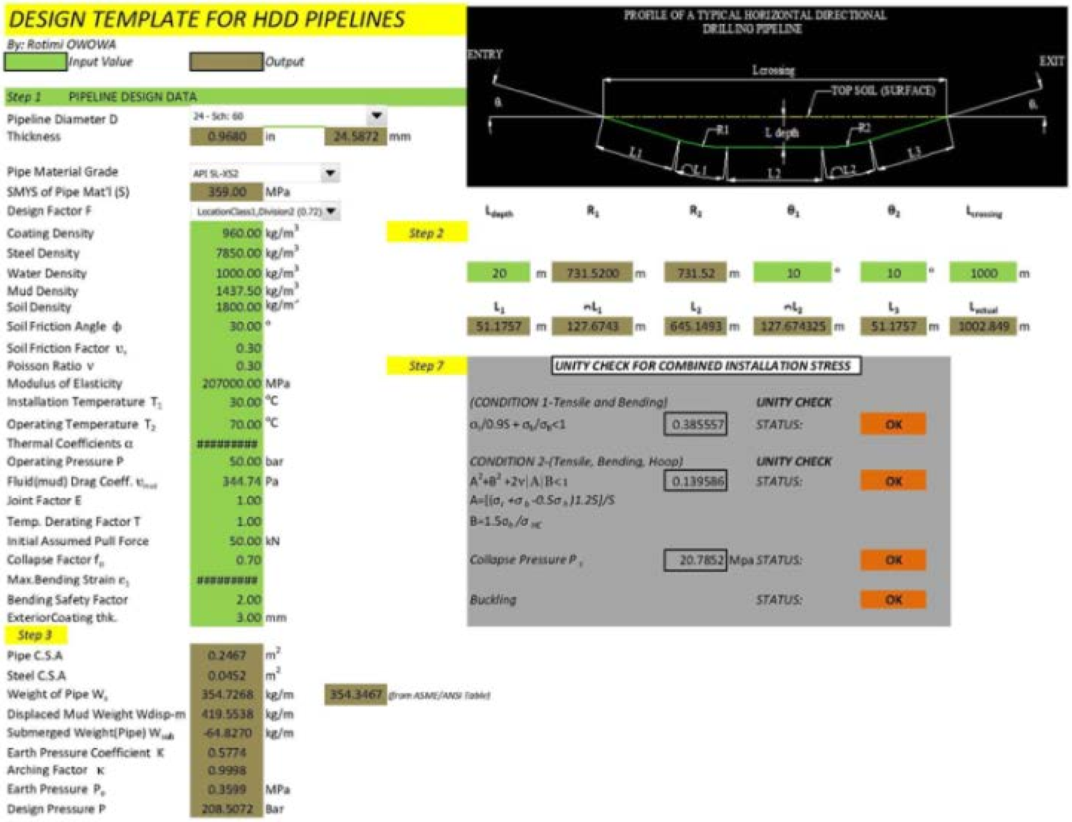

Figure 3. Installation Design Template for HDD Pipeline

- **Bending stress:**

Aspect Ratio D/t - 24.7934; $\dfrac{1500000}{S}$ - 28.8082; Bending Stress σ_b - 86.25 MPa; Allowable σ_B (since D/t < $\dfrac{1500000}{S}$) - 269.25 MPa; Status ($\sigma_b \le \sigma_B$) – Satisfactory.

- **Buckling and External Hoop Stress:**

Earth Pressure $P'_e = \kappa\rho_s H$ - 0.3599MPa; Collapse Pressure $P_c = \dfrac{P_y P_e}{\sqrt{P_y^2 + P_e^2}}$ - 20.7852 MPa; Buckling Strain $\varepsilon_b = \left(\dfrac{t}{2D}\right)$ - 0.0202; Ovality δ (Based on 1% Diameter variation) $\dfrac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}}$ - 0.0050; Collapse Reduction Factor g(δ) -0.9095; Bending Strain ε $\dfrac{\varepsilon}{\varepsilon_b} + \dfrac{(P_o - P_i)}{f_o P_c} \le g(\delta)$ - 0.0174; Buckling (Combined bending and Ext Pressure $f_1\varepsilon_1$) - 0.0030; Buckling Status $\varepsilon \ge f_1\varepsilon_1$ – Satisfactory; External Hoop Stress $\sigma_h = (P_o D)/(2t)$ - 4.4620 MPa; Elastic Hoop Buck Stress $\sigma_{he} = 0.88E(t/D)^2$ - 296.3338 MPa; Allowable σ_h, $\sigma_{he}/1.5$ - 198.5437 MPa; Status ($\sigma_h \le \dfrac{\sigma_{he}}{1.5}$) – Satisfactory.

- **Combined Stress**

Tension and Bending (Unity check 1)

$\dfrac{\sigma_t}{0.9S} + \dfrac{\sigma_b}{\sigma_B} = 0.3856 \le 1$ - Status is satisfactory;

Tension, Bending and Hoop (Unity check 2) $A = \left[(\sigma_t + \sigma_b - 0.5\sigma_h)1.25\right] / S$ - 0.3731; $B = 1.5\sigma_h / \sigma_{hc}$ - 0.0018, For ν = 0.3, check $A^2 + B^2 + 2\nu|A|B = 0.1396 \le 1$ hence status is satisfactory.

- **Operating Stress**

Internal/Operating Pressure P - 50bar (5.0000 MPa); Internal Hoop Stress $\sigma_{hi} = (P_i * D)/(2 * t)$ - 61.9835 MPa; Bending Stress $\sigma_b = (E * D)/(2 * R)$ - 86.2500 MPa; Thermal Stress $\sigma_e = E\alpha(T_2 - T_1)$ - -96.8760 MPa.

- **Combined Operating Stress**

Total Circumferential Stress $\sigma_c = \sigma_h - \sigma_{hi}$ - 8.0999 MPa; Longitudinal Stress $\sigma_l = \sigma_e + \sigma_b + (\nu \times \sigma_c)$ - -8.0999 MPa; Allowable longitudinal Stress $(0.90S)$ - 323.1000MPa; Status $(\sigma_l \le 0.90S)$ - Satisfactory; Maximum Shear Stress $\sigma_v = (\sigma_c - \sigma_l)/2$ - 88.7280 MPa; Allowable Shear stress ($0.45S$) - 161.5500 MPa; Status ($\sigma_v \le 0.45S$) – Satisfactory.

Since the results meet all design criteria specified, it is therefore safe (based on the stated assumptions)to proceed with the installation without risk of failure. For a pulling load of about 1000kN, a rig of about 100 ton is adequate for the installation. The Pulling load obtained corroborates the results obtained by using Pipeline Tool Box 2012®

3.2. Analysis

3.2.1. Depth versus External Pressure Analysis

The curve of external pressure P_o variation with pipeline burial depth H is shown in Figure 4.

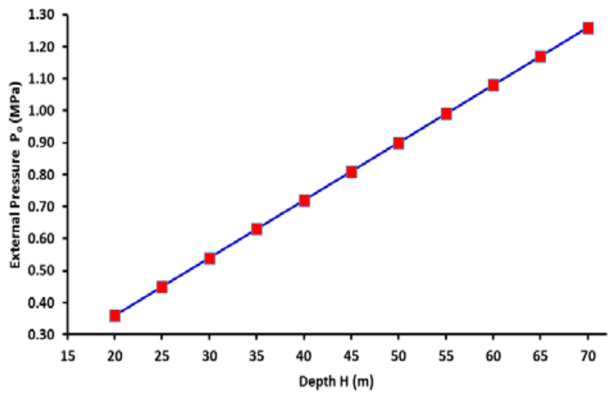

Figure 4. Depth of Burial, H (m) versus External Pressure, P_o (MPa) variation (check ($P_o < P_c$ = 20.79MPa)

It can be seen from the results that the depth of burial has minimum impact on the installation as the external pressure is less than collapse pressure (20.7852 MPa) for the pipe material.

3.2.2. Tensile Stress versus Combined Installation Stress Factor (CISF)

Tensile Stress contributes most significantly to the combined installation stress because the bending stress, whose value depends on the radius of curvature and entry angle for the installation, is constant. The relationship between the tensile Stress and the Combination Stress Factor (Unity Check) is presented in Figure 5.

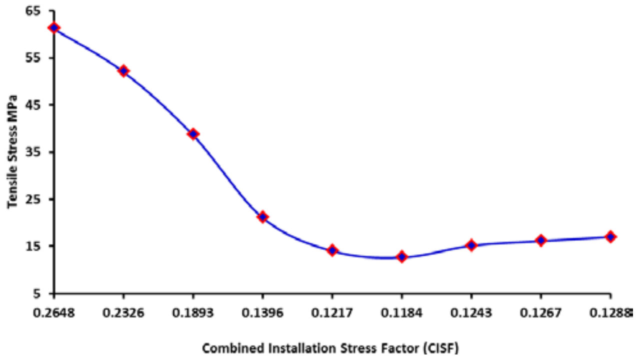

Figure 5. Tensile Stress analysis vs. Combined Installation Stress (Unity Check) Factor Analysis (CISF < 1)

This results shows that there is a direct relation between Tensile Stress and Combined Installation Stress. A higher Tensile Stress will result in higher CISF and may exceed acceptable limit.

3.2.3. Material grade versus Combined Installation Stress Factor Analysis

Figure 6 shows the Material grade (strength) relationship and CISF, using a constant diameter 610 mm (24”) and wall thickness 24.59 mm with other installation conditions remaining constant.

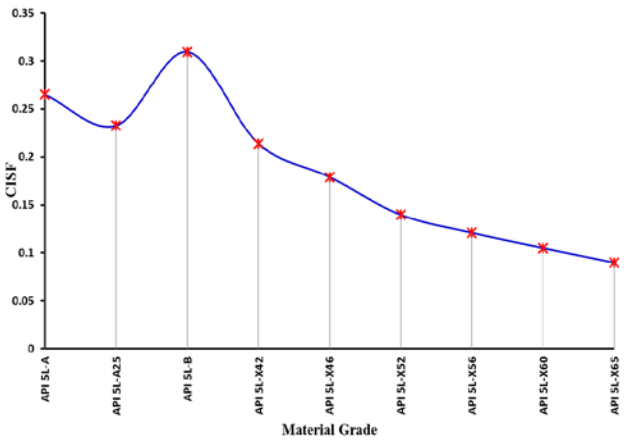

Figure 6. Combined Installation Stress Factor (CISF) Analysis versus Material grade

The result shows that for the given diameter and wall thickness, the material grade should not be less than API 5L-X42.

3.2.4. Wall Thickness versus Tensile Stress versus CISF

For the given material grade API 5L-X52, a variation of the Pipe Schedule (wall thickness) was carried out to investigate the appropriate material match for the installation as in Figure 7.

From Figure 6 it is observed that for the selected material grade (API 5L-X52), a wall thickness lower than 24”-Sch 60 will fail during installation. A safe optimum design can however be obtained if a higher material grade would be used for smaller wall thicknesses.

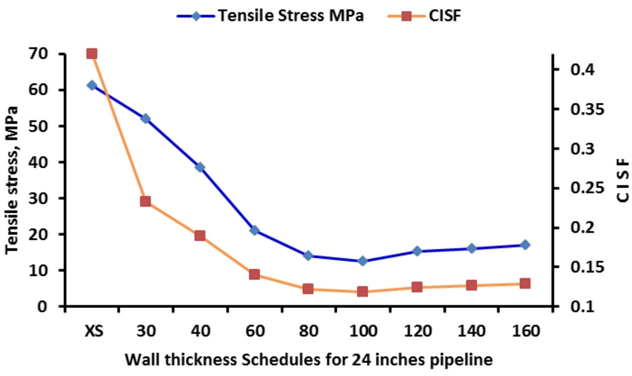

Figure 7. Wall thickness versus tensile Stress and CISF (for 24-in Pipe)

3.2.5. Entry Angle versus Tensile Stress and CISF

The relationship between HDD Entry angle, the Tensile Stress and CISF is presented in Figure 8. It was observed that for pipe diameter of size 20”-24”, the installation entry angle should not be greater than 14°. Higher diameter pipes should not exceed 12° [13].

Within the acceptable range of entry angles for a given diameter, entry angle significance on tensile stress is minimal. However, an attempt to exceed the specified entry angle shows a log normal relationship with tensile Stress.

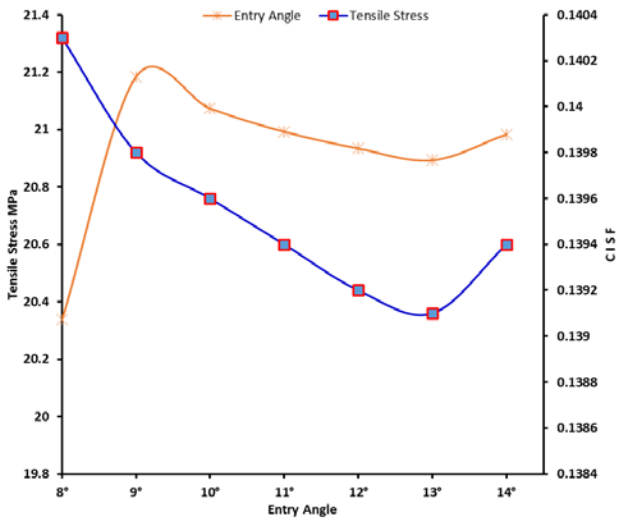

Figure 8. Entry Angle versus tensile Stress and CISF

3.3. Discussion of Findings

The primary objective of pipeline design is to optimize the relationship between pipe diameter, material, wall thickness, appurtenances, economics, constructability and operability.

From the various analyses, the benchmarks (Pass or Fail) for key design parameters used in simulating the design template were found. The design optimization was performed based on project specification (case study) and simulated with the design Template developed. From the results obtained the optimum design is Material Grade – API 5L-B, wall thickness 24”- Sch XS, tensile stress 61.0188MPa, CISF – 0.5859, entry angle – 10°.

It was found that while API 5L-X52 was specified as the material grade for the installation, analyses show that API 5L-X42 would sufficiently meet the design and operating conditions However, if environmental changes and higher operating parameters is a possibility for the pipeline in the future, API 5L-X52 is recommended.

4. Conclusions

The equations which reliably describe the installation and operational stresses induced on a pipeline installed by Horizontal Directional Drilling (HDD) have been solved. A user friendly Installation Design Template for the analyses of Collapse, Buckling and Installation Forces has been developed on Microsoft Excel® platform. These forces have been simulated and analyzed to establish the acceptable load and stress limits for deep buried HDD pipelines. The results obtained showed that tensile stress due to the pulling load is the most significant variable affecting the Combined Installation Stress Factor. Also, the installation entry and exit angles for pipe diameter greater than 500mm should be limited to less than 12°. To reduce the bending stress in the curved sections, the installation hole radius of curvature R should be $R \geq 1200D$.

Symbols and Notations

A_s - *Cross-sectional Area of Steel, [m²]*
A_p - *Internal Area of Pipe, [m²]*
A - *Coefficient of thermal linear expansivity*
B - *Silo width (Reamed Hole Diameter), [m]*
D - *Nominal Diameter, [m]*
D_{max} - *Maximum External Diameter, [m]*
D_{min} - *Minimum External Diameter, [m]*
D_o - *Outer Diameter, [m]*
σ_c - *Total Circumferential Stress, [N/m²]*
σ_b - *Bending Stress, [N/m²]*
σ_e - *Thermal Stress, [N/m²]*
σ_B - *Maximum Allowable be Bending Stress, [N/m²]*
σ_h - *Hoop Stress due to External Pressure, [N/m²]*
σ_{hi} - *Hoop Stress due to internal Pressure, [N/m²]*
σ_{hc} - *Critical Hoop Buckling Stress, [N/m²]*
σ_{he} - *Elastic Hoop Buckling Stress, [N/m²]*
σ_l - *Longitudinal Stress, [N/m²]*
σ_t - *Tensile Stress, [N/m²]*
δ - *Ovality*
E - *Young Modulus of elasticity, [N/m²]*
F_D - *drag between pipe and drilling fluid, [N]*
ε - *Bending strain in pipe,*
ε_b - *Buckling Strain under Pure bending*
f_o - *Collapse Factor*
f_1 - *Bending Factor*
F - *Design Factor,*
$g(\delta)$ - *Collapse Reduction Factor*
h - *Displacement of Circular arc, [m]*
H - *Depth of Cover, [m]*
I - *Moment of inertia*
K - *Earth Pressure Coefficient*
K - *Arching Factor*
L_{arc} - *Length of arc, [m]*
L - *Length of Pipe Section*
$L_{crossing}$ - *HDD horizontal crossing distance, [m]*
$\frown L$ - *Arc Length, [m]*
N - *Normal Reaction, [N]*
Φ - *Angle of Friction*
ρ_s - *Pipe density, [kg/m³]*
ρ_s - *Soil Density, [kg/m³]*

ρ_m - *Mud Density, [kg/m³]*
P - *Operating Pressure, [N/m²]*
P_d - *Design Pressure, [N/m²]*
Θ - *Angle of Inclination*
Fric - *friction force between pipe and soil.*
P_c - *Collapse Pressure, [N/m²]*
P_o - *External Hydrostatic Pressure, [N/m²]*
P_i - *Internal Pressure, [N/m²]*
P_e - *Elastic Collapse Pressure, [N/m²]*
P_y - *Yield Pressure at Collapse, [N/m²]*
R - *Radius of Curvature, [m]*
S - *Specified Minimum Yield Strength, [N/m²]*
T - *Tension, [N]*
T_1 - *Installation Temperature, [°C]*
T_2 - *Operating Temperature, [°C]*
t - *Wall thickness, [mm]*
T_{est} - *Estimated Tension, [N]*
v - *Poisson Ratio*
υ_{soil} - *Soil Coefficient of Friction*
υ_{mud} - *Mud Coefficient of Friction*
W_{disp-m} - *Displaced Mud Weight, [kg]*
W_p - *Weight of Pipe, [kg]*
W_{sub} - *Submerged Pipe Weight, [kg]*
σ_v - *maximum shear stress, [N/m²];*
σ_c - *total circumferential stress, [N/m²]*
σ_l - *total longitudinal stress, [N/m²]*

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