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Static Analysis of Submerged Pipeline at Varying Water Depths

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Abstract:
Background: Stresses, tensions and pressure associated with submerged offshore structural pipeline under the influence of water depth affects the laying process. The static effects of increasing seawater depths needs to be determined to minimize its effects on the pipeline and prevent the collapse of the operation.
Materials and Methods: X65 bare pipe was used in the analysis at varying water depths from 500m to 2500m, excel spreadsheet software also was used in the analysis with stress, pressure and tension model equations.
Results: The results gotten showed that as the hydrostatic external pressure and the tensions acting on the pipeline increases (3027625Pa, 475084N to 25138125Pa, 1955420N) for the pressure and vertical tension respectively, the depth of the seabed increases.
Conclusion: This shows that the depth of the seawater is important in pipe-laying analysis on offshore pipeline.
Key Word: Tensions, Stresses, Axial force, Hydrostatics Pressure, Seabed, Stinger, Pipeline.

I. INTRODUCTION

The analysis of offshore structural pipeline during installation requires the computation of stresses, internal forces and deformations due to loads from external sources. The length of the pipeline determines its behaviour in water. For short pipeline it is like a body that is rigid while that of a longer pipe it is like string and elastic which depends on the depth of the water. The analysis of pipeline structure is like beam that is continuous with a tension member, external loads, compression member, suppression elements and pressure. The static effects of the stresses, tension and hydrostatic pressure on the pipeline needs to be determined as the seawater depths varies from 500m to 2500m to ensure that its effects on the line is minimized to prevent the collapse of the operation. In pipe-laying process, the tension on the pipeline should be kept in a safe level, hence, the need to analyse the effect of the seawater depth on the tension holding capacity of the system to minimize the tension on the line during laying process[1].

Pipeline monitoring

The monitoring of the pipe laying processes requires various parameters depending on the vessels size, depth of its operation and the methods used in the pipeline installation that needs to be checked. The processes include:

- Vessels position and velocity
- Axial tension
- Departure angle
- Touch-down position
- Roller pressure
- Distance to last roller
- Free-span pipe length
- Water depth
- Environmental loads
- Touchdown distance[2].

The static analysis of the pipeline can only be determined when the material properties used in the pipe is known and it depends on the capability of the laying vessels equipment in computing the parameters in the pipe-laying operations such as the roller box height, stinger departure angle, initial tension, the ideal radius of the stinger, and also checking the stress and strains of the pipeline for acceptable limits. The tension in the pipelaying vessel can be manipulated when the installation is ongoing, since it is only the parameter that can be tempered with base on its relationship with the depth of the seabed and the departure angle. The axial tension on the pipeline is of two directions, the vertical and the horizontal direction. The vertical component is controlled by the depth of the sea and the weight of the pipe and compensated by the restoring forces of the pipe-laying vessel while the horizontal component is controlled by the motion of the pipe-laying vessel control system[3].

Pipe stressed regions

The region from the tension equipment across the stinger up to the top of the stinger that is supported fully is known as the over-bend region. An over-bend strain is produced by the stinger radius that must be checked to know if it meets the allowable level for strain in pipe internationally. When the region is having a high over-bend strain, it causes twisting and potential rotation on the seabed during the installation of the pipeline. The issue of local loads on stinger cannot proceed out of the inflection point and this over-bend region is not found in the J-lay method[4, 5].

The sag-bend is the area from the stinger to the point of touch-down in which the pipe centre line is below the radius of curvature, the load that affects the pipeline in the sag-bend are the tension on the pipe, submerged weight of the pipe, the bending stiffness and the external pressure, all of which are the static load effects on the submerged pipeline. There are no boundaries to which the pipeline can experience deformation and make the sag-bend necessary for the entire installation method in deep water the same[4].

The intermediate region is from the lift off point of the stinger to the inflexion point and it is not supported fully by the stinger. This region is very difficult to analyse, hence the use of the stinger-tip region for the analysis. The stinger-tip region is from the third-last roller to the inflection point that constitutes this region. The intermediate region is determined separately due to the dynamic bending loads on the last roller[6].

The pipeline tension is very important in solving the issues in pipe laying operation in the S-lay and J-lay methods of pipe laying operation, having static axial tension in equilibrium with lift angle of θ. The methods of the vessel control system for both cases are shown in Figure 1 for the S-lay and J-lay respectively. The horizontal tension is being counteracted in the J-lay installation positioning system while that of the S-lay installation, the stinger force acts on the pipe in which the positioning system of the vessel counteract the horizontal component of the reaction force S_H of the stinger and the tension at the bottom, all of which are summed[7].

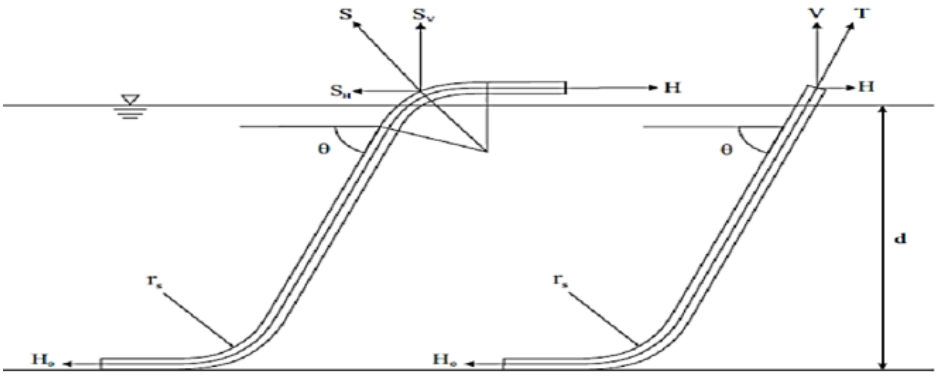

Figure 1: S-lay and J-lay Pipe-laying Operations[8].

Where
Ho = Horizontal bottom tension
H (S_H) = Horizontal top tension
V (S_V) = Vertical tension
T (S) = Effective tension
r_S = Radius of curvature
θ = Departure angle (lift off angle)
d = Seawater depth

The ideal tension, elastic beam theory and buoyancy forces in pipe laying

The issue of tension in pipe laying operation is very important for the safety and stability of the operation. Low tension reduces free spans and yield short radii on the segment that is curved. Also, excessive tension is dangerous to the pipe laying operation as it will result to over-bending and plasticizing (ovalization) of the pipe. When the tension is low the seabed preparation will be reduced and also, too low tension will cause the buckling of the pipe. This is why most pipe laying installation is done with empty pipe to reduce the tension during installation. The dynamic parameters in pipe laying operation are the tensions which are being affected by the pipeline boundary conditions and environmental loads. The pipe laying vessels orientation and position is taken as the upper boundary conditions while the touchdown point orientation and position are taken as the lower boundary condition, the loads acting on the pipeline during installation are operational, gravitational, environmental and constructional loads which are classified as either static or dynamic[2].

In the elastic deformation of the pipe, there are internal forces such as shearing, bending and twisting that opposes the external applied forces which keep the body in a state of equilibrium. When the internal and external forces are the same, the pipe will return to its original state un-deformed when the external applied forces are removed. But when the applied external forces are greater than the internal forces, it will result to permanent deformation of the pipe as shown in Figures 2 and 3 for the S-lay and J-lay respectively and causes structural failure of the pipe material which is also called buckling of the pipe or plastic deformation that the pipe cannot return to its original state when the external applied forces are removed. When the pipe leaves the pipe laying vessel from the stinger during installation, the deformation of the pipe is linearly elastic which obeys Hooke's law and relates the deformation in the stress (σ) and strain (ε) of the material[9].

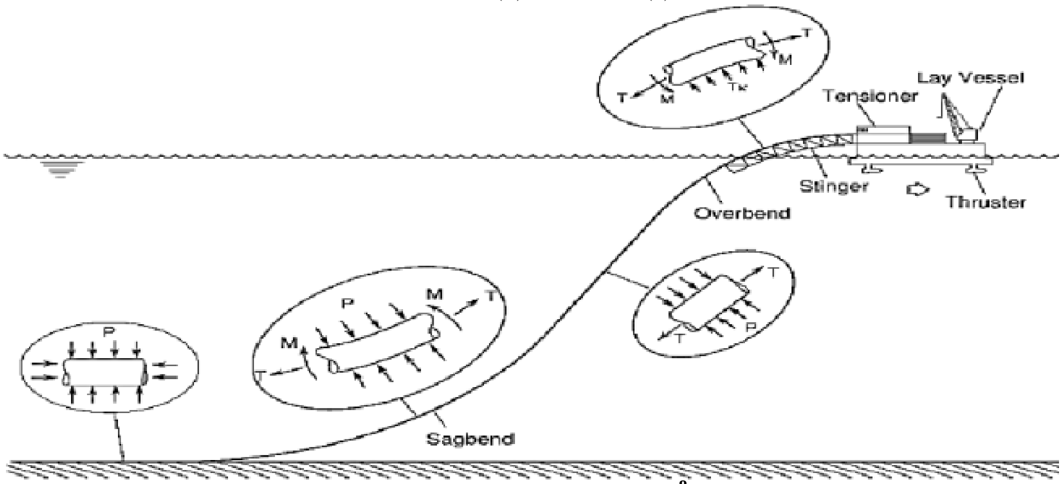

Figure 2: S-lay Deformation[8]

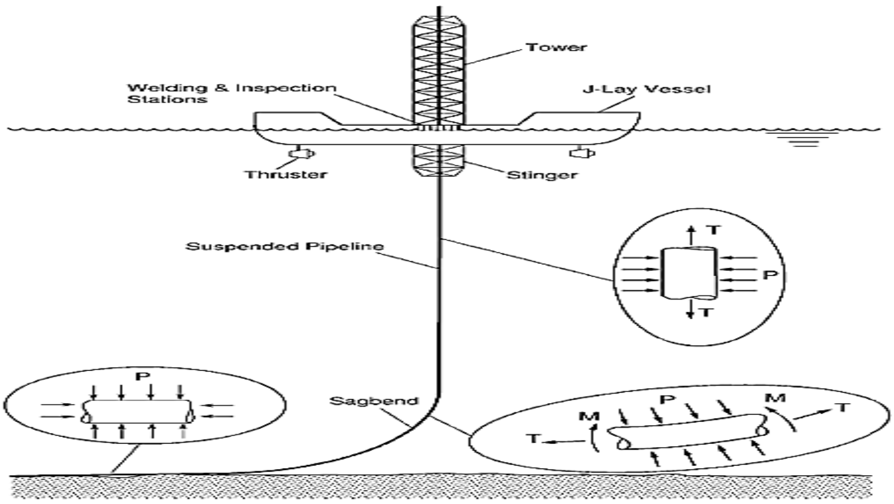

Figure 3: J-lay Deformation[8]

The pipeline in the pipe laying process is taken to be empty and the dry unit weight of the pipe 'w_d' is a function of the mass of the pipe and its acceleration due to gravitational force, it is similar to the unit force as a result of gravity. From Archimedes when a body or an object is submerged fully or partly in water, there will be an upward force that acts on the body due to the water pressure known as up thrust which must be equal to the weight of the fluid displaced. This hydrostatic force being experienced by the body in water is called buoyancy force. The buoyancy is acting at the centroid that is corresponding to the centre of gravity because there is no movement produced on the body by the buoyancy force. This law cannot be used for computing a body that is partly submerged with fully closed pressure field. The issue of buoyancy will be different for the pressure fields of partly submerged pipe with open ends of the pipe segment[10].

II. MATERIALS AND METHODS

The pipe that was used in this analysis was an X65 bare pipe of thickness of about 0.011m at varying (500m to 2500m) seawater depths. The data that were used in the course of this study are as shown in table 1 and equations 1 to 20 were the modeled equations used in excel spreadsheet for the analysis.

Table 1: Pipe Parameter[11, 12]

S/N	Parameters	Values
1	Carbon steel pipe	20 inch (0.508m)
2	Density	7850kg/m^3
3	Youngs modulus	2X 105MPa
4	Passion's ratio	0.3
5	Ovality	1.50%
6	Maximum overbend strain	0.50%
7	Tension capacity	105000N
8	Sea density	1.025kg/m^3
9	X65 Pipe	448MPa (MYS)/530MPa (MTS)
10	Seawater depth	500m, 1000m, 1500, 2000m 2500m
11	Seabed friction (x y direction)	0.3
13	Pipe thickness (Bare pipe)	11mm (0.011m)
15	Elongation	18%

Modeled equations

Weight of the submerged pipe (Ws)

The weight of the submerged steel pipe for this research study is calculated using (1), the parameters of the pipe are as follows:

$$W_s = \frac{\pi}{4}[(d_o^2 - d_i^2)(\rho_s - \rho_w)]g \quad (1)$$

Outside diameter (d_o) = 20" = 0.508m
Steel pipe thickness (t) = 0.011m
Inside diameter (d_i) = 0.497m
Steel pipe density (ρ_s) = 7850kg/m^3
Sea water density (ρ_ω) = 1025kg/m^3 [10]

Suspended length of pipe

The suspended pipe length for S-lay operation is shown in (2), this equation was used in the calculation of the suspended length of the pipe at various water depths ranging from 500m to 2500m respectively.

$$L = \frac{H}{\omega_S}\left[\left(\frac{D\omega_S}{H} + 1\right)^2\right]^{1/2} \quad (2)$$

Where
L = Length of suspended pipe
D = Water depth

Vertical tension acting on the pipe

The vertical tension and that of the top tension force acting on the S-lay pipe was calculated as given and as shown in (3) and (4)[7].

$$V = W_s L \quad (3)$$
$$T = \sqrt{H^2 + V^2} \quad (4)$$

Minimum lay tension

The minimum lay tension that is needed in the pipeline laying operation was calculated with (5).

$$T_m = R \text{ x } W_s \text{ x } \mu \quad (5)$$

Where
μ = Coefficient of friction on the seabed (0.3)
R = Radius of turn along pipeline route (800m)
T_m = 800 x 740.168 x 0.3 = 177640.32N

The pipeline touchdown distance

The pipeline touchdown distance for the S-lay operation was calculated for various pipe lengths as given in (6).

$$x = {}^{H}/_{\omega_c} \sin h^{-1}\left(\frac{V}{H}\right) \quad (6)$$

Where
x = Touchdown distance

Strain in the say-bend and over-bend region for the S-lay pipe operation
The sag-bend (8) and over-bend region (9) strain for the S-lay laying operation was calculated with (7) to (9) for various water depths.

$$R = \frac{H}{W_s} \quad (7)$$

$$\varepsilon_{max} = \frac{d_o/_2}{R} \quad (8)$$

$$\varepsilon_{max} = \frac{d_o W_s}{2H} \quad (9)$$

Where
R = Bending radius of 141.8597m

Static stress analysis of the pipeline

The stresses that affect the pipe under water during pipe laying operations and the related hydrostatic pressure can be determined with (10) to (18) respectively

$$h_s = \frac{H}{W_s}\left(\cosh\frac{xW_s}{H} - 1\right) \quad (10)$$

Where
h_s = Stinger tip height above seabed

$$\frac{1}{R} = \frac{W_s}{H} \quad (11)$$

Where
R = Radius at touchdown point

$$P_O = \rho_\omega g\, D \quad (12)$$

P_O = Hydrostatic external pressure

$$\sigma_b = \pm E\,\frac{d_o}{2R} \quad (13)$$

Where
σ_b = The bending stress

$$\sigma_h = -P_o\frac{d_o}{2t} \quad (14)$$

Where
σ_h = The hoop stress
t = Pipe thickness

$$F_a = V - W_s D - P_o\, {}^1/_4\, \pi\,(d_o + 2t)^2 \quad (15)$$

Where
F_a = Axial force

$$A = \pi\left(\frac{d_o}{2}\right)^2 - \pi\left(\frac{d_o}{2} - t\right)^2 \quad (16)$$

Where
A_s = Cross sectional area of pipe

$$\sigma_a = \frac{F_a}{A} \quad (17)$$

Where
σ_a = The axial stress on the pipe

$$\sigma_L = \sigma_a \pm \sigma_b \quad (18)$$

Where
σ_L= The longitudinal stress on the pipe[13].

Equivalent stress and pressures acting on the pipeline

The (19) to (23) was used in the analysis of the equivalent stress, critical collapse pressure (P_c), full plasticity pressure (P_y), propagation buckling (P_p) and the strain acting on the pipe line for S-lay operation.

$$\sigma_{eq} = \sqrt{\sigma_h^2 - \sigma_L\sigma_h + \sigma_L^2} \quad (19)$$

$$P_c = \frac{2E}{1-v^2\left(\frac{d_o}{t}\right)^2} \quad (20)$$

$$P_y = 2\sigma_y\left(\frac{t}{d_o - t}\right) \quad (21)$$

$$P_P = 10.7\sigma_y\left(\frac{t}{d_o}\right)^{2.25} \quad (22)$$

$$\varepsilon = \frac{\sigma_{a,h}}{E} \quad 2 \quad (23)$$

III. RESULTS PRESENTATION

The analysis of the results was done using Microsoft excel spreadsheet program for the simulation of the given data. Figures 4 to 11 show the results of the suspended length of the pipe, the vertical and top tension acting on the pipe, the touchdown distance, stinger tip above seabed and various forces, stresses and strain acting on the pipe at various sea water depth from 500m to 2500m.

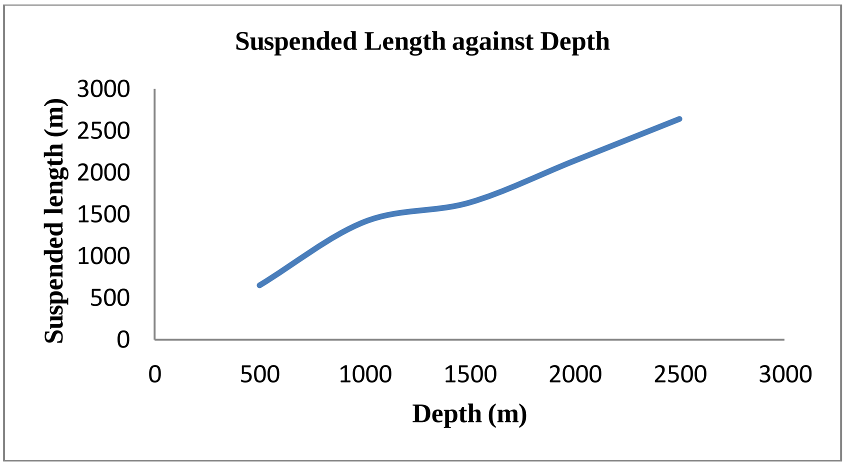

Figure 4: Suspended Length of the Pipe against Water Depth

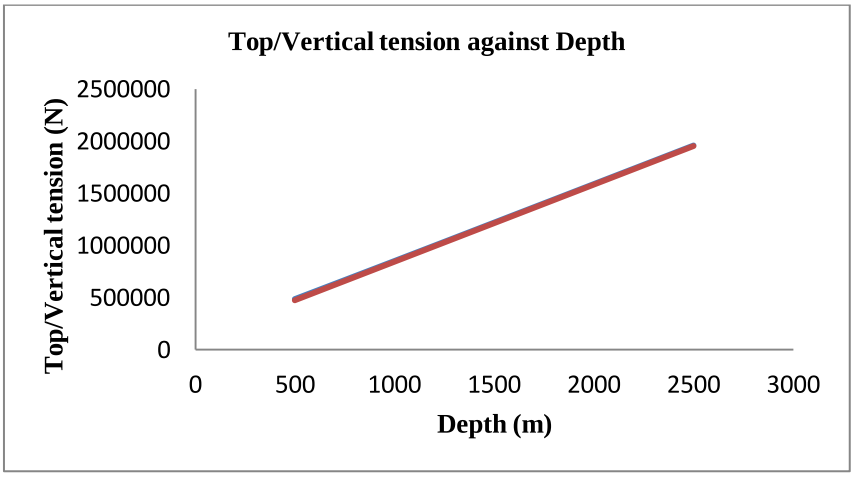

Figure 5: Vertical and Top Tension against Water Depth

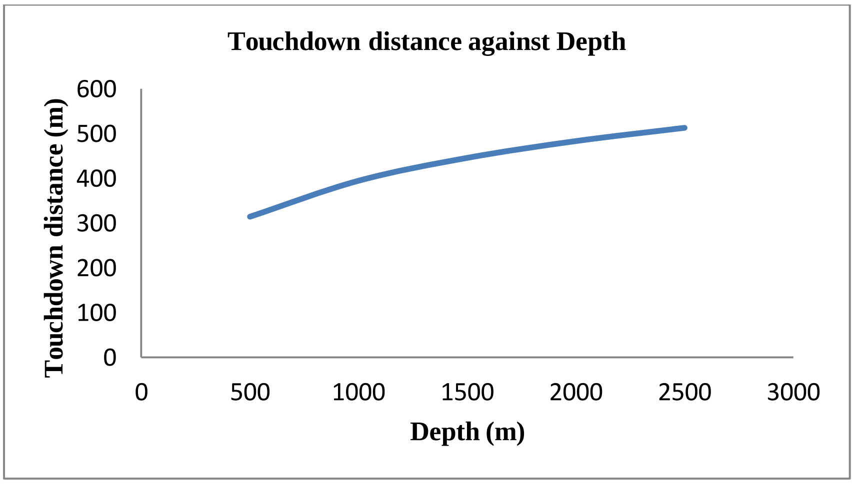

Figure 6: Touchdown Distance against Water depth

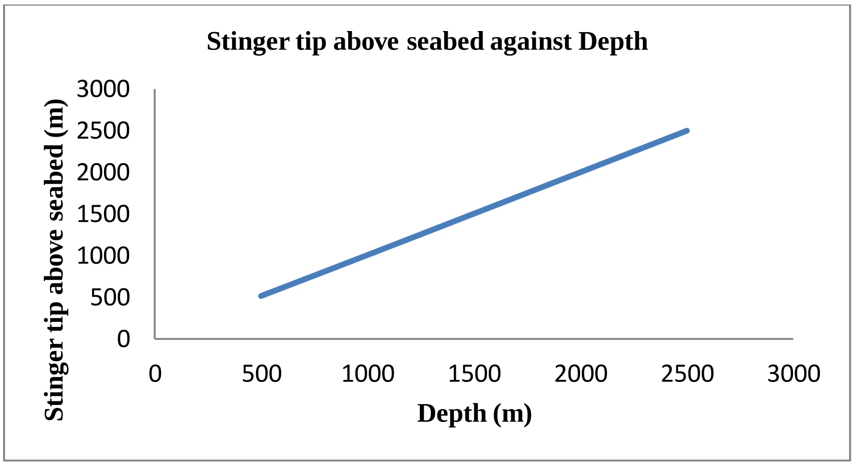

Figure 7: Stinger Tip above Seabed against Water Depth

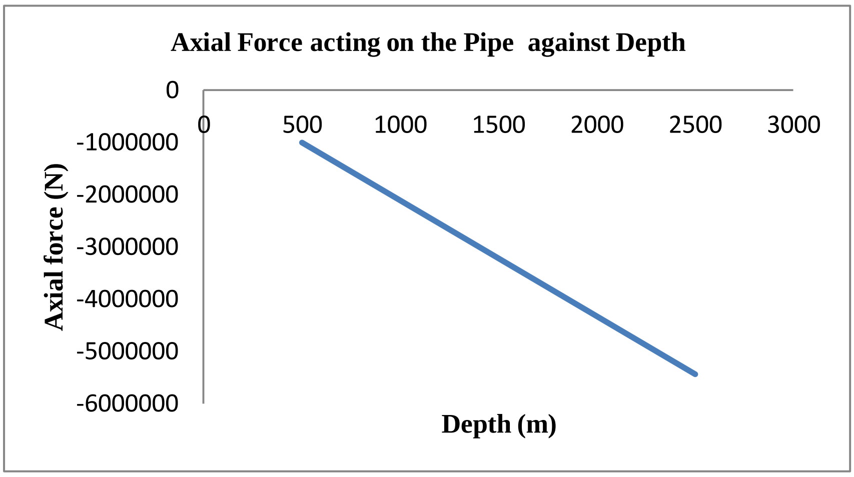

Figure 8: Axial Force against Water Depth

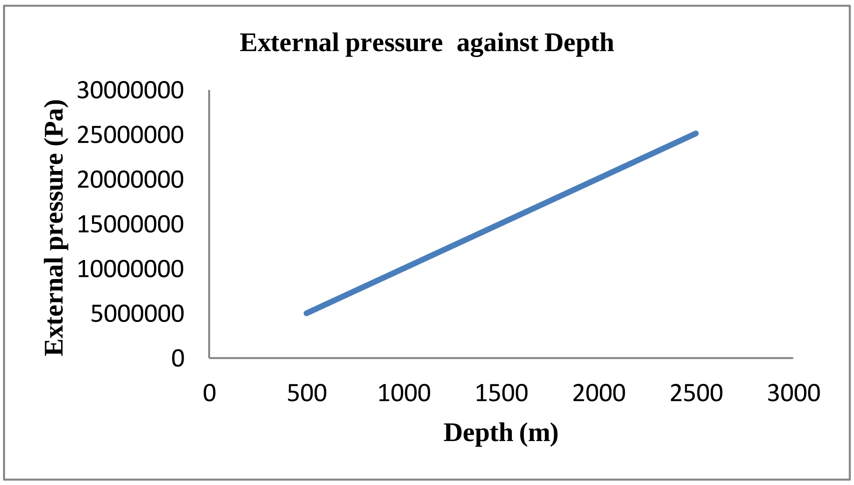

Figure 9: Hydrostatic Pressure against Water Depth

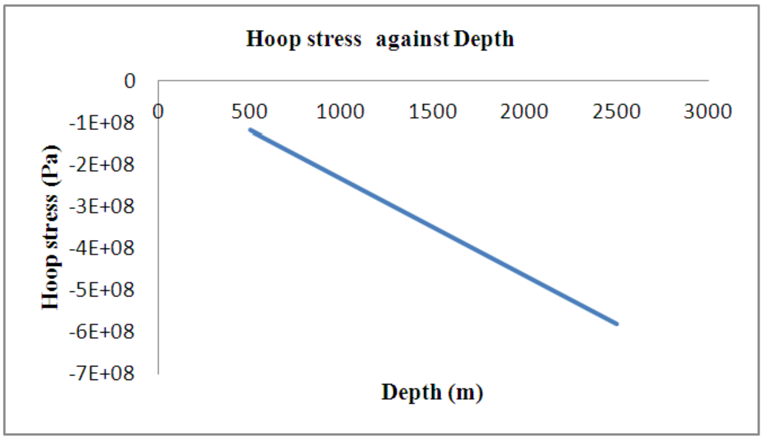

Figure 10: Hoop Stress against Water Depth

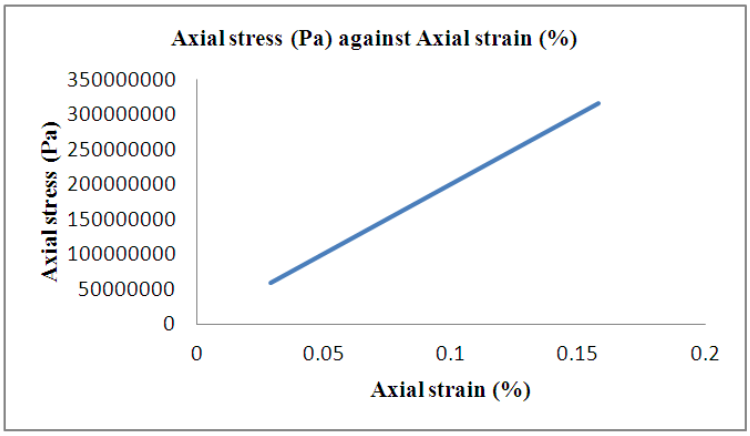

Figure 11: Equivalent Stress against Water Depth

IV. DISCUSSION OF RESULTS

The suspended length of the pipe attached to the pipe laying vessel was analysed as shown in figure 4 to know its effect when the depth of the seabed increases, it shows that as the seabed increases from 500m to 2500m, the suspended length of the pipe increases also from 641.8597m to 2641.8597m respectively. The suspended length increases almost linearly from 500m (641.8597m) to 1000m (1411.8597m) where it changes its linearity as the depth of the seawater increases. This increase causes loss of the pipeline due to the effect on the over-bend region strain increase and collapse of the pipeline when environmental load act on it. The stinger used in the laying operation should have enough buoyancy and curvature to support the extra weight of the pipeline due to increased span length and depth.

The vertical and top tension which was analysed on the pipeline as shown in figure 5, shows that there was no difference in the analysed forces as the depth of the seawater increases from 500m to 2500m. The vertical and top tension acting on the pipe at this water depth are 475084N and 486548.8743N which increases linearly to 1955420N and 1958237.058N for water depth of 500m and 2500m respectively. The vertical and top tension of the pipe are the same and increases in the same proportion as the depth of the seabed increases showing that the tension acting on the pipe both on the vertical and top part have to balance each other for the stability of the operation. The vertical and the top tension needed for the smooth operation of the pipe laying process must be increased as the depth of the seabed increases and also the dynamic lay effect is weaken.

The touchdown distance of the pipe at the bottom of the seabed during pipe laying operation was analysed as shown in figure 6, the values of the touchdown distance increases linearly as the depth of the seabed increases from 500m to 2500m of which the touchdown distance recorded for this depth was 314.1727m to 513.2863m respectively. The rise of touchdown distance was much from 500m depth to 1500m depth of which the touchdown distances are 314.1727m, 394.7329m and 445.9721m respectively but the increase from the 1500m depth to the 2500m depth was minimal (445.9721m, 483.5760m and 513.2863m respectively). This shows minimal effect on the touchdown distance when there was further increase in the depth of the sea depth beyond the 2500m depth. It causes large indentation when the tension is low during pipe laying operation. Also, depending on the type of seabed and soil stiffness, the touchdown distance affects the fatigue life of the lay pipeline.

The stinger tip above the seabed was analysed as shown in figure 7, the tip above seabed during operation increases as the depth of the seabed increases but at constant proportion. At 500m seabed depth, the stinger tip above seabed was 515.4896m which increase to 1008.7783m as the water depth rises to 1000m and at 2500m depth, the stinger tip above the seabed was 2503.8060m of which the average rise on the stinger tip above seabed is 497.33m. The depth of the seabed affects the stinger tip above the seabed, by increasing the depth, the stinger tip was also increased showing that depth increase increases the tip, this shows an increase in the submerged length of the pipeline and the applied tension needed to contain the load.

The axial force acting on the pipe during pipe laying activities as shown in figure 8, was analysed with varying water depth. Increased seabed depth affects the axial force acting on the pipeline, from the depth of 500m, the axial force was -1004186.302N which decreased linearly in the negative x-axis as the water depth increases to 1500m (-3222558.905N), at a depth of 2000m it falls to about -4331745.207N. The axial force acting on the pipe was -5440931.508N at a depth of 2500m, which shows that as the depth of the seabed increases, the axial force acting on the pipe underwater decreases. Increasing compressive axial force can results to failure of the pipeline by buckling laterally, this deflection helps to reduce the axial loads acting on the pipeline**.**

The hydrostatic external pressure acting on the pipe increased steadily in the positive x-axis as the depth of the seabed increases from 500m (5027625Pa) to 2500m (25138125Pa). This shows that with increased depth of the sea, the effect of the hydrostatic pressure on the pipe during the pipe laying operation was much. The external hydrostatic pressure can result to permanent deformation of the submerged pipeline when the pressure exceeds its critical value and subsequent failure of the pipeline. The pressure developed externally is safe for the smooth operation of laying pipeline since it was below the critical collapsed pressure (206099313.30Pa), but above the full plasticity and the propagation pressure for the pipeline, the hydrostatic external pressure still maintains its integrity as seen in figure 9.

The hoop stress shows a constant drop as the depth of the seabed increases from 500m to 2500m linearly in the negative x-axis as shown in figure 10. The stress decreases steadily from the 500m depth up to the 2500m depth of which the recorded values are -116092431.8Pa, -232184863.6Pa, -348277295.4Pa, -464369727.3Pa and -580462159.1Pa respectively. The hoop stress protects the pipeline from bursting if it does not exceed the maximum yield strength of the material used in the manufacturing of the pipeline. From the analysis, the maximum yield strength the X65 pipe can hold to maintain its stability is about 344960000Pa which was less than the values recorded from the analysis showed that the pipeline was in a stable condition.

The axial stress and strain acting on the pipeline were analysed as the depth of the seabed increases from 500m to 2500m as shown in figure 11. It shows a constant linearly drop as the depth of the seabed increased from 500m to 2500m of which the recorded data for the axial stress and strain are 58382924.52Pa (0.029), 122870500.20Pa (0.061), 187358075.90Pa (0.094), 251845651.60Pa (0.126) and 316333227.20Pa (0.158) respectively, the strain was under the maximum over-bend strain region (0.5%) and the steel material was still in the plastic region.

V. CONCLUSION

The effect of the pipe-laying vessel forces analysis was based on the water depth effect of the stresses affecting the pipeline system. From the findings and the simulations of the forces, stresses and pressure, it was found that the suspended length of the pipe increases as the depth of the sea water increases, that of the vertical and top tension acting on the pipe during pipe-laying operation increases as the depth of the water increases. The touchdown distance on the seabed increases but minimal as the water depth increases, while that of the over-bend (0.1791%) and the sag-bend (0.1791%) strains are below the critical (0.5%) region, and the stinger tip above seabed increases as the water depth increases. The hoop stress, axial force, equivalent stress and strain were also discussed, the hoop stress axial force decreases as the depth of the seabed increases while that of the equivalent stresses and strain on the pipeline increases and the depth of the seabed increases, this show that the seawater depth plays a vital role in pipe-laying process.

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