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Pipeline End Manifold (PLEM) Structural Response Analysis due to the Settlement Process

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ABSTRACT

Pipeline End Manifold (PLEM) is an offshore structure that consists of a simple subsea manifold that combines two or more pipelines into one pipeline. Like other offshore structures, the risk of seabed settlement may occur, and settlement is predicted can increase the stress of pipe and frame members. Stress that exceeds the allowable stress of codes may be a danger. So, stress analysis of the UC ratio of pipe and frame PLEM due to the settlement must be done. Stress analysis is performed using the numerical method with the model in FEM software. UC ratio refers to AMSE B31.8 2010 for pipe and API RP 2A (WSD) 22ed 2014 for the structural frame. From this analysis, the allowable settlement of pipe codes is at a depth below 450.42 mm. The deeper the settlement, the more stress the member frame increases. At a depth of 600 mm settlement, the greatest stress, 133.125 N/mm^2, UC 0.375, is found on member E04(L). According to the pipe codes, the maximum slope is 2.27˚ on the southward slope. The biggest effect of tilt settlement on the member frame is found in the west direction at member E04(U) with a value of 244.6 N/mm^2, UC 0.689, tilt settlement 3˚.

Keywords: *Settlement, Tilt Settlement, PLEM, Pipe Stress Analysis, Structural Frame Stress Analysis*

1. INTRODUCTION

Pipeline End Manifolds (PLEM) are subsea structures (simple manifolds) set at the end of a pipeline that is used to connect rigid pipelines with other subsea structures, such as a manifold or tree, through a jumper [1]. PLEM is used to combine two or more pipelines and eliminate the need for additional risers [2].

Like other offshore structures, the risk of seabed settlement may occur, and settlement is predicted can increase the stress of pipe and frame members. Stress act on the structure must not exceed codes allowable stress for allowable stress on the structural frame, which refers to API RP 2A (WSD), and for pipelines, the system refers to ASME B31.8 or DNV OS F-101 [3]. Wind, wave, and current design loads should be based on a design return interval no less than five times the design life of the pipeline or 100 years, whichever is smaller [4]. Stress that acts on the pipeline system before and after settlement must do to compare the operational stress.

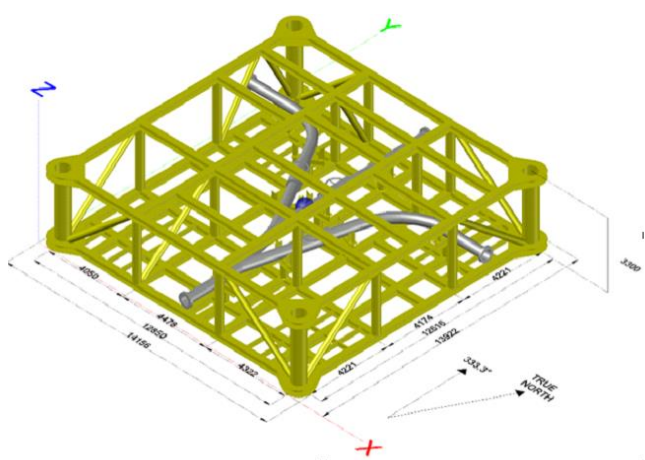

Figure 1. Pipeline End Manifold (PLEM) Illustration

2. RESEARCH DESCRIPTION

2.1 Study Literature and Data Collecting

Step for reading and collecting references and collecting data for research. Data needed are structure, pipe, and environment data.

2.2 Modelling and Validating Model

The pipe and structure model is divided, each modeled in finite element software for global stress analysis. Then, the environmental loads are inputted into the model. After that, the model weight and center of gravity are compared to the actual structure for validation. If the model error is below 5%, the model is valid.

2.3 Pipeline System UC Analysis

UC pipeline analysis was done on FEM software with codes ASME B31.8 2010. The stress of pipelines is affected by the pipe's temperature, pressure, and bending. This stress affects the strength of the pipelines during operation, so it is necessary to calculate the allowable stress of the pipeline according to the codes. These stresses are as follows;

2.3.1 Hoop Stress

Hoop stress is the stress that acts around the pipe wall, caused by internal pressure and the external pressure of the pipe. The equation is as follows;

For $D/t \geq 30$

$$S_h = (P_i - P_e)\frac{D}{2000t} \text{ [4]} \quad (1)$$

For $D/t < 30$

$$S_h = (P_i - P_e)\frac{D-t}{2000t} \text{ [4]} \quad (2)$$

2.3.2 Longitudinal Stress

Longitudinal stress is caused by thermal, pressure, and bending effects on the pipe. For pipe classification, the author uses restraint (buried in a ditch or placed on a seabed).

Longitudinal stress caused by Internal Pressure. Equation;

$$S_p = 0{,}3S_h \text{ [4]} \quad (3)$$

Longitudinal stress is caused by thermal expansion. Equation;

$$S_T = E\alpha(T_1 - T_2) \text{ [4]} \quad (4)$$

The normal bending stress on straight pipe (run pipe) or long radius bending is caused by weight or other external loads. Equation;

$$S_B = M/Z \text{ [4]} \quad (5)$$

The normal bending stress on fittings and pipe components cause by weight or other external loads. Equation;

$$S_B = M_R/Z \text{ [4]} \quad (6)$$

Stress is caused by axial load besides thermal expansion and pressure. Equation;

$$S_B = R/A \text{ [4]} \quad (7)$$

The combined stress equation can refer to two theories, Von Mises and Tresca. Following equations;

Von Mises (*Distorsional Energy*)

$$({S_h}^2 - S_L S_h + {S_L}^2 + 3{S_t}^2)^{1/2} \leq F_3 S \text{ [4]} \quad (8)$$

Tresca (*maximum Shear Stress*)

$$2\left[\left(\frac{S_L - S_h}{2}\right)^2 + {S_t}^2\right]^{1/2} \leq F_3 S \text{ [4]} \quad (9)$$

2.4 Structural Frame UC Analysis

In-place analysis was carried out to know the effect of the stress obtained between the pipe and clamps on the condition of the PLEM operating. The analysis was carried out on finite element-based software and referred to the codes API RP 2A (WSD) 22nd edition of 2014. The equation for the cylindrical member is as follows;

$$\frac{f_a}{0.6F_y} + \frac{\sqrt{f_{bx}^2 + f_{by}^2}}{F_b} \leq 1.0 \quad \text{[5]} \quad (10)$$

For $f_a/Fa \leq 0{,}15$

$$\frac{f_a}{F_a} + \frac{\sqrt{f_{bx}^2 + f_{by}^2}}{F_b} \leq 1.0 \quad \text{[5]} \quad (11)$$

2.5 Regression and Correlation Analysis

Regression analysis is used to study and measure the statistical relationship between two or more variables. In contrast, correlation analysis is an analysis that aims to determine "how strong" or "degree of closeness," a relationship that occurs in variables [6]. The analysis' input uses UC stress during settlement, and the output is displayed in a graph of the results.

2.5.1 Simple Linear Regression

Here is a simple linear regression equation;

$$\hat{y} = a + bx \text{ [6]} \quad (12)$$

$$b = \frac{n(\sum xy) - (\sum x).(\sum y)}{n(\sum x^2) - (\sum x)^2} \text{ [6]} \quad (13)$$

$$a = \bar{y} - b.\bar{x} \text{ [6]} \quad (14)$$

2.5.2 Polynomial 2nd order Regression

Here is a polynomial 2nd-order regression equation;

$$\hat{y} = a2.(x^2) + a1.(x) + a \quad (15)$$

$$\begin{bmatrix} n & \sum x & \sum x^2 \\ \sum x & \sum x^2 & \sum x^3 \\ \sum x^2 & \sum x^3 & \sum x^4 \end{bmatrix} \begin{bmatrix} a \\ a1 \\ a2 \end{bmatrix} = \begin{bmatrix} \sum y \\ \sum x.y \\ \sum x^2 y \end{bmatrix} \quad (16)$$

2.5.3 Correlation

The correlation equation for simple linear regression and a polynomial 2nd-order is;

$$r^2 = \frac{\sum(\hat{y} - \bar{y})^2}{\sum(y - \bar{y})^2} \text{ [6]} \quad (17)$$

3. DISCUSSION RESULTS

3.1 Structure, Pipeline, and Environment Data

The pipeline end-manifold (PLEM) analyzed by the authors operates in a gas field in Mottama Bay off the coast of Myanmar. The PLEM structure has an orientation of 333.6 (T) from the true north. PLEM is operated at a depth of 159,600 m. PLEM combines three 18" pipes from wellhead platforms 2, 8, and 19 to 1 18" pipe to the production quarter. PLEM structure data for this analysis is divided into two sections: the pipeline system and the structural frame. Other components not in that section are modeled as weight in the structural frame model. Below is the structural frame illustration;

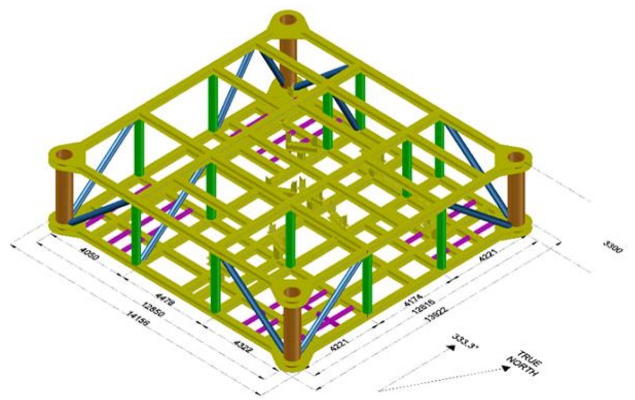

Figure 2. Structural Frame PLEM illustration

Table 1. Structural Frame PLEM Data

Components	Dsc.	Size (mm)	Material
H Beam		H 300 x 300 x 94	S355 JR+AR
Tubular ø273,1		D = 273,1 t.= 9,27	S355 JR+AR
Tubular ø406,4		D = 406,4 t.= 12,7	S355 JR+AR
Tubular ø711,2		D = 711,2 t.= 25,4	S355 JR+AR
Channel		C 200 x 80 x 7,5 x 11	S355 JR+AR

The pipeline has fittings and components such as three valves, two wyes, four flanges, and nine pipe clamps for this analysis. Support pipe clamps limit pipe movement at the z-axis and the y-axis perpendicular to the pipe, but for the y-axis, the pipe can move until 200mm to the left and right. Clamps do not limit pipe movement for the x-axis perpendicular to the pipe. The illustration is in figure 4.

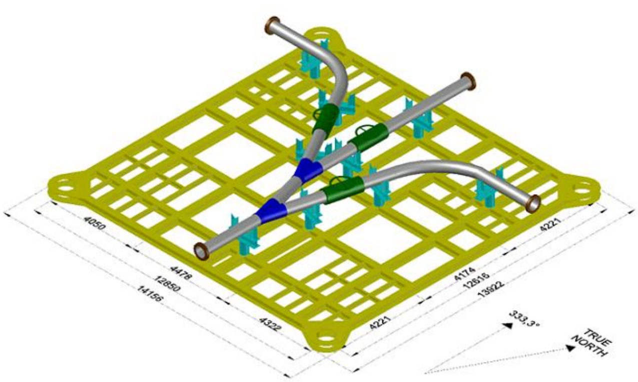

Figure 3. Pipeline System on Lower Frame PLEM

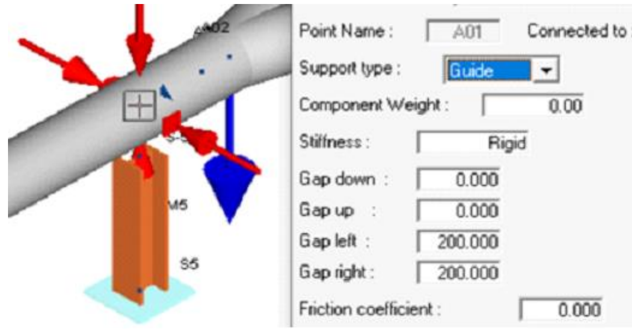

Figure 4. Pipe Clamp Illustration

Table 2. PLEM Pipe Data

	General		***Unit***
1	*Nominal Pipe Size*	18	*Inch*
2	*Wall Thickness*	19,1	mm
3	*Material Grade*	API 5L X65	-
	Service Condition		*Unit*
4	*Corrosion Allow.*	10	mm
5	*Design Pressure*	70	barg
6	*Design Temp.*	Min.-10 / Max. 116	˚C
7	*Design Flowrate*	200	MMSCFD
8	*Seawater Temp.*	Min. 19 / Max. 19,7	˚C
9	*Water Depth*	158,45	M
10	*Product Density*	Min. 17,4 / Max. 653,6	Kg/m^3
11	*Seawater Density*	1025	Kg/m^3

The problem limitation is the pipe design temperature of 60˚C, Product density of 653.6 Kg/m3, and seawater temperature of 19.7˚C for this analysis.

3.2 Model Validation

Because no mass and COG validation exceeds 5%, it can be said that the PLEM pipeline system and structural frame model are valid.

Table 3. Pipeline System PLEM Model Validation

Table Pipeline System PLEM Model Validation					
Mass (Kg)		**Actual**	**22085,40**	**Error Mass**	**3,62%**
		Model	**22885,83**		
COG (mm)	X	Actual	7279,43	Error COG	0,16%
		Model	7290,77		
	Y	Actual	7857,71		1,48%
		Model	7741,58		
	Z	Actual	1400,00		0,0%
		Model	1400,00		
				Error COG	0,54%

Table 4. Structural Frame PLEM Model Validation

Table Structural Frame PLEM Model Validation					
Mass (Kg)		**Actual**	**60141,23**	**Error Mass**	**2,70%**
		Model	**61765,00**		
COG (mm)	X	Actual	7109,67	Error COG	0,56%
		Model	7070,00		
	Y	Actual	7101,77		0,54%
		Model	7140,00		
	Z	Actual	1459,88		1,4%
		Model	1440,00		
				Error COG	0,82%

3.3 Pipeline System Stress Analysis Due to Settlement

The settlement model varies with the settlement unit in mm, and the seabed under the structure is considered flat. The results of the UC pipeline analysis are summarized in tables 5 and 6.

UC Graph on Point A-01(Design Pressure)

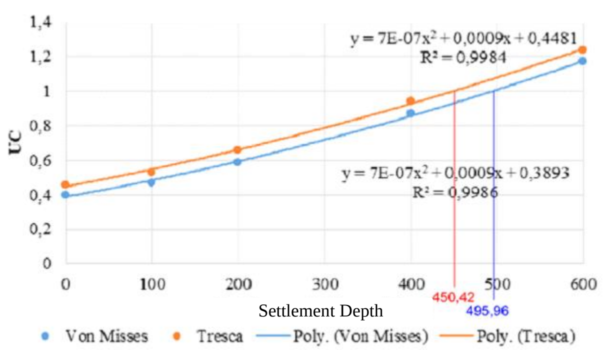

Figure 5. Graph of Point with Highest UC (Point A-01) When Settlement

Allowable Combined Stress 403.2 N/mm2, due to the allowable factor in the codes for pipelines combined stress = 0.9 × yield strength.

Table 5. UC Ratio of Pipeline Due to Settlement (*Design Pressure* Von Mises Theory)

UC Ratio of Pipeline Due to Settlement (*Design Pressure* Von Mises Theory)						
***Settlement* (mm)**		**0**	**100**	**200**	**400**	**600**
View Points	A-01	0,4	0,47	0,59	0,87	1,17
	B19	0,18	0,26	0,37	0,61	0,86
	D06	0,26	0,39	0,53	0,84	1,14
	E17	0,16	0,25	0,38	0,65	0,93

Table 6. UC Ratio of Pipeline Due to Settlement (*Design Pressure* Tresca Theory)

UC Ratio of Pipeline Due to Settlement (*Design Pressure* Tresca Theory)						
***Settlement* (mm)**		**0**	**100**	**200**	**400**	**600**
View Points	A-01	0,46	0,53	0,66	0,94	1,24
	B19	0,2	0,3	0,42	0,67	0,93
	D06	0,3	0,44	0,6	0,9	1,21
	E17	0,16	0,29	0,43	0,71	1

The highest stress is obtained at point A-01 (pipe support on the seabed). The allowable settlement (UC<1) is less than 450.42 mm in terms of Tresca theory and less than 495.96 mm in Von Mises theory. An illustration of the UC pipe at a settlement of 600 mm is in the attachment of Figure 14.

3.4 Structural Frame Stress Analysis Due to Settlement

Settlement is indicated that can increase stress on the member frame because of the pipe support at the lower frame. Some clamps limit pipe movement. The results of the software global fem analysis are as follows.

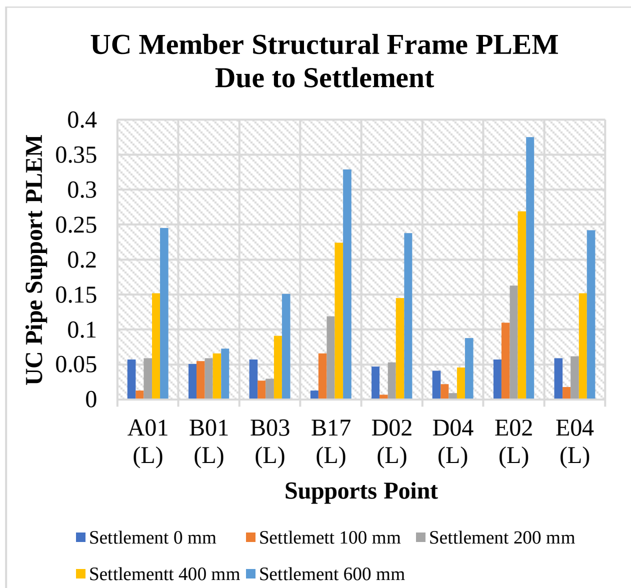

Figure 6. UC Member Structural Frame PLEM Due to Settlement

The member with the greatest stress is member E04(L), with a value of 133.125 N/mm2 (UC = 0.375) in the 600 mm settlement variation sample. In this condition, the structural frame still meets the codes (UC below 1). At this depth, the structure is still safe to operate.

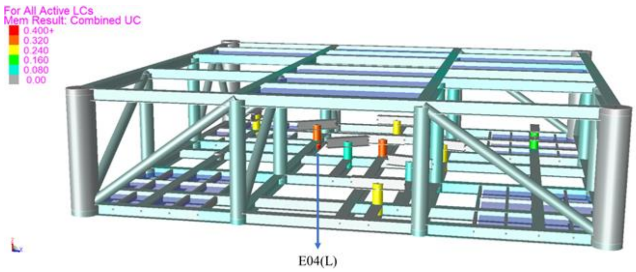

Figure 7. Illustration of Max Combined UC Structural Frame Due to Settlement

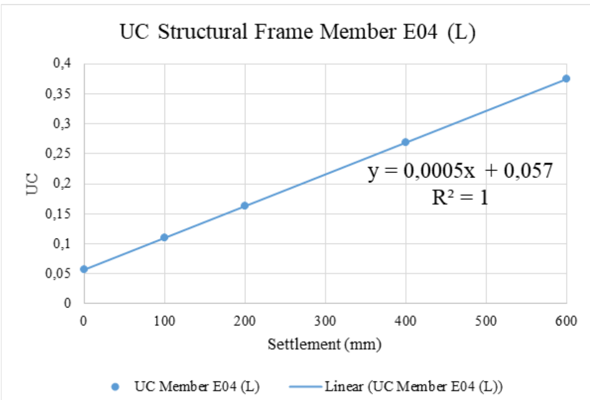

Figure 8. Graph of UC on Member E04(L) When Settlement

3.4 Pipeline System Stress Analysis Due to Settlement

Pipeline stress analysis was carried out in 8 directions of tilt settlement according to the cardinal points. The direction of the slope follows the north of the structure, not the true north. In this analysis, the stress on a slope of 3˚ is reviewed, and then the direction with the greatest stress is chosen.

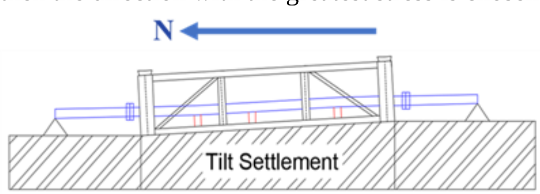

Figure 9. Illustration of Tilt Settlement Northward Slope

The results are summarized in a diagram of four points with the highest UC in each direction of tilt settlement in Figure 9. Then the analysis is carried out again in the direction of south-tilt settlement because the UC value is the largest. The analysis was carried out to determine the safe limit of the slope because, at tilt settlement 3˚ southward, the UC exceeds 1. The samples taken are 0˚, 1˚, and 3˚. The allowable combined stress pipelines for Tresca and Von Mises theory is 403.2 N/mm2.

The greatest stress is found at point A(01) with the allowable stress (UC<1) at a slope below 2.27˚ when viewed with Tresca theory and below 2.5˚ when viewed with Von Mises theory. The UC graph at point A(01) is in Figure 11, and the UC Global illustration is in Figure 15.

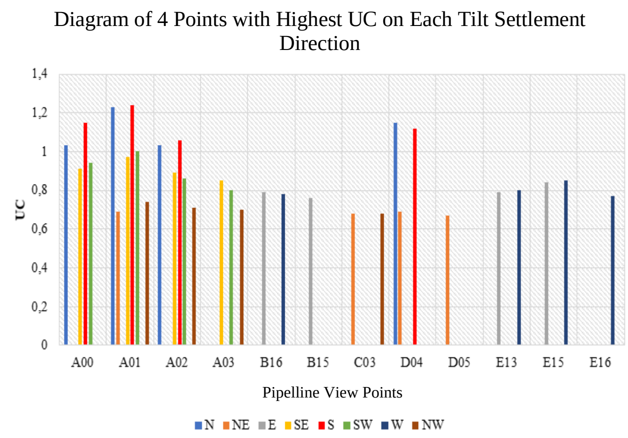

Figure 10. Diagram of 4 Points with Highest UC on Each Tilt Settlement Direction

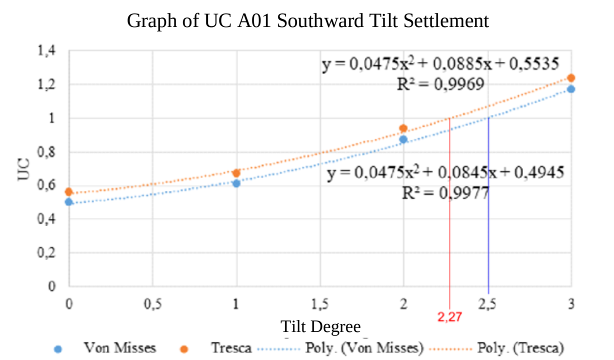

Figure 11. Grafik UC Point A01 of *Pipeline System* Due to Southward *Tilt Settlement*

3.5 Structural Frame Stress Analysis Due to Settlement

The greatest stress between the pipe and the support clamps caused by tilt settlement with a slope of 3˚ is in the west. The member who is exposed to the greatest stress is member E(04), with a value of 244.6 N/mm2 (UC = 0.689), safe according to codes (UC < 1).

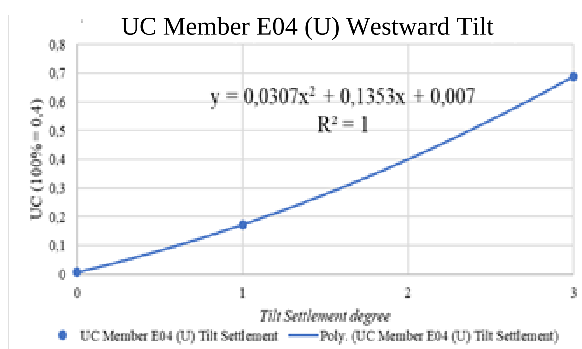

Figure 12. Graph of UC Member E04 (U) Westward Tilt Settlement

Figure 13. is the result of the UC structural frame output from the FEM software.

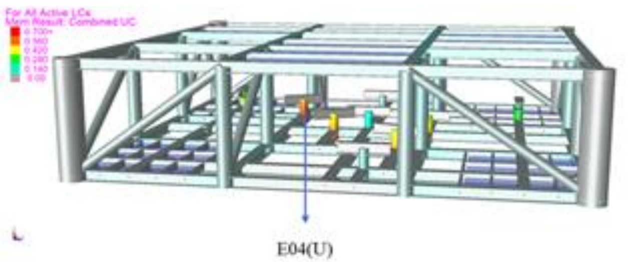

Figure 13. Illustration of Max Combined UC Structural Frame Due to Southward Tilt Settlement

4. CONCLUSIONS

Settlement depth affects the stress of the PLEM pipeline system, where the stress continues to increase at a depth of 0-600 mm. The critical point is A-01 with pipe stress that still meets the codes (UC<1) at a depth of 450.2 mm in terms of Tresca's theory.

The settlement affects the structural stress of the frame, where at a depth of 0-600 mm, the stress support of the frame continues to increase. Member E04(L)/member 0189-0080 experienced the greatest stress, with a value of 133.125 N/mm2 (UC = 0.375) at 600 mm settlement. In this condition, the structural frame still meets the codes (UC<1).

Tilt Settlement affects the increase in stress on the pipe. From the 8 variations in the direction of the tilt settlement slope at an angle of 3˚, the largest pipe stress is found in the south direction at point A01 with a slope that is still allowed codes (UC<1) 2.27˚ in terms of Tresca's theory.

The pipe load also affects the stress on the structural frame members due to the tilt settlement process, where the highest value is at member E04(U)/member 0080-0097, and tilt settlement towards the west is 3˚. The stress value is 244.6 N/mm2 (UC = 0.689), declared safe according to codes (UC<1).

APPENDIX

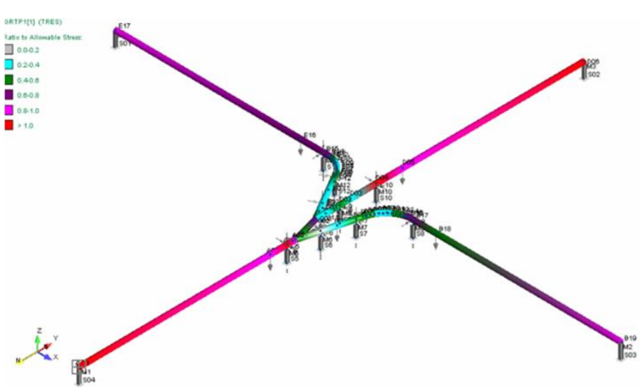

Figure 14. UC *Settlement* 600 mm *Design Pressure* (Tresca)

Table 8. UC Member PLEM on Settlement Variations

UC Member						
***Settlement* (mm)**		**0**	**100**	**200**	**400**	**600**
Member View Points	A01 (L)	0.057	0.013	0.059	0.152	0.245
	B01 (L)	0.051	0.055	0.059	0.066	0.073
	B03 (L)	0.042	0.083	0.124	0.205	0.287
	B17 (L)	0.057	0.027	0.03	0.091	0.151
	D02 (L)	0.013	0.066	0.119	0.224	0.329
	D04 (L)	0.047	0.007	0.053	0.145	0.238
	E02 (L)	0.041	0.022	0.09	0.206	0.307
	E04 (L)	0.057	0.11	0.163	0.269	0.375
	E17 (L)	0.059	0.018	0.062	0.152	0.242

Table 9. Four Points with Highest UC on Tilt Settlement 3˚ (Tresca)

4 Points with Highest UC on *Tilt Settlement* 3˚(Tresca)								
View Points	**Tilt Directions**							
	N	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
A00	1,03			0,91	1,15	0,94		
A01	1,23	0,69		0,97	1,24	1		0,74
A02	1,03			0,89	1,06	0,86		0,71
A03				0,85		0,8		0,7
B16			0,79				0,78	
B15			0,76					
C03		0,68						0,68
D04	1,15	0,69			1,12			
D05		0,67						
E13			0,79				0,8	
E15			0,84				0,85	
E16							0,77	

Table 10. UC *Member Structural Frame Westward Tilt Settlement*

UC Member Westward Tilt Settlement				
Settlement		0	1	3
Member View Points	A01 (L)	0,057	0,034	0,06
	A01 (U)	0,036	0,015	0,052
	B01 (L)	0,051	0,183	0,485
	B01 (U)	0,022	0,17	0,553
	B03 (L)	0,042	0,143	0,441
	B03 (U)	0,003	0,142	0,505
	B17 (L)	0,057	0,125	0,294
	B17 (U)	0,028	0,106	0,307
	D02 (L)	0,013	0,067	0,187
	D02 (U)	0,005	0,066	0,193
	D04 (L)	0,047	0,045	0,047

Table 11. Formula Descriptions

Symbol	Descriptions	Units
D	Pipe Outer Diameter	mm
t	Pipe Wall Thickness	mm
S_h	Hoop Stress	MPa
P_i	Internal Pressure	kPa
P_e	External Pressure	kPa
S_p	Longitudinal Stress Due to Internal Pressure	Mpa
S_T	Longitudinal Stress Due to Thermal Expansion	MPa
T_1	The temperature when Installing, Tie-end, or Burring	˚C
T_2	Operating Temperature	˚C
E	Modulus Elasticity, Ambient Temperature	MPa
α	Thermal Expansion Coeficient (1/˚C)	-
M	Bending moment pipe cross-section	N.m
Z	Pipe Section Modulus	cm^3
S_B	Bending Stress	MPa
M_R	The resultant intensified moment on all fittings or components	N.m
S_x	Axial load stress, besides thermal expansion and pressure	MPa
R	Components External Axial Loads	N
A	Pipe Cross Section Area	mm^2
S_L	Longitudinal stress net	MPa
S_t	Torsional Stress	MPa
S	Minimum Yield Strength	MPa
F_3	Combined Stress Factor	-
fa	Axial Compressive Stress	as per API
fbx	Bending Stress X-Axis	as per API
fby	Bending Stress Y-Axis	as per API
Fy	Yield Strength	MPa
Fb	Allowable Bending Stress	as per API
Fa	Allowable Axial Compressive Stress	as per API
$\hat{y}$	Estimate Value of Dependent Variable	-
a	The Intersection of the Regression Line on the y-Axis	-
b	The gradient of the Regression Line	-
x	Value of Independent Variable	-
n	Sum of Points (Observation pairs (X, Y))	-
r^2	Coefficient of determination	-

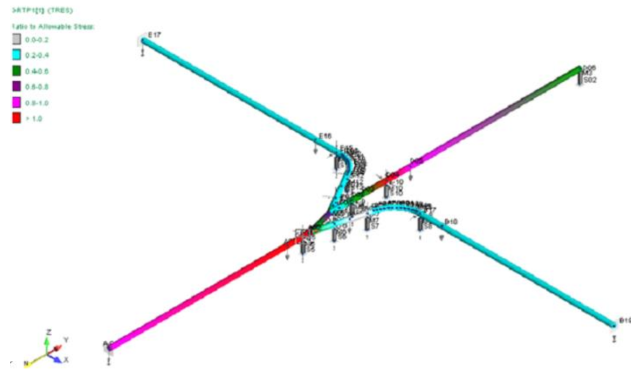

Figure 15. UC Southward (S) *Tilt Settlement* 3˚ (Tresca)

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