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Pipe Stacking Optimization and Sea Fastening Analysis of Linepipe Transport

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ABSTRACT

Subsea pipeline is a system comprised of multiple linepipes that are welded when installed on location used to distribute fluid such as oil and natural gas. Fabricated linepipes are to be stacked on cargo barge and transported to the installation location. This operation takes significant time and involves numerous linepipes. Optimization needs to be done to make sure the transport operation is executed efficiently. Optimization attempt was done using data from Double Joint Linepipe Transport Operation of Tangguh Expansion Project by Saipem Indonesia. Parameters considered during the optimization process include linepipe qualities during stacking, cargo barge strength and stability, and sea fastening property strength. Roark's Formulas for Stress and Strain formulas are used in pipe stacking analysis to find stacking limit for each type of linepipes. Stability analysis is done by using DNVGL-ST-N001 as a guide and Maxsurf software for modelling. SACS software is used to analyzed sea fastening properties with guidance from DNVGL-ST-N001. Finally, optimization is done using a multi-criteria optimization method by using values from each analysis as parameters. Optimization results find that pipe stacking method using side support is 8.41% more optimal than standard pipe stacking method from Saipem Indonesia.

Keywords: *Linepipe, Optimization, Pipe stacking, Sea fastening, Stability*

1. INTRODUCTION

Subsea pipelines are used commonly on the oil and gas industry to distribute fluids extracted from oil or natural gas fields. These systems consist of many joints of smaller pipes called linepipes. Linepipes are fabricated in fabrication or production facility and transported to the intended location to be installed by welding it to each other and create length pipeline system. Transport operation of linepipe usually takes days to weeks involving a large number of linepipes. With all this in mind, linepipes are stacked on cargo barge for efficient transport by maximizing cargo barge capacity.

Not only stacked, linepipes are sea fastened with slings and other sea fastening properties to ensure the cargo safety during the passage, restricting movement such as rolling so that the linepipes stays on a cargo barge. Using Transport Operation from Tangguh Expansion Project by Saipem Indonesia as a study case, this research is aimed to optimized pipe stacking method and provide alternative methods different from previous transport operation. The goal of this research is to determine the most optimized method of pipe stacking for Double Joint Linepipe Transportation Operation for Tangguh Expansion Project by Saipem Indonesia.

Optimization was done using multi-criteria optimization method, a method of optimizing based on multiple criteria which are defined by using utility function [1]. Parameters to be considered for optimization process are linepipe qualities, cargo barge strength and stability, and sea fastening property strength. Linepipe qualities are considered by pipe stacking analysis, using API RP 5LW as international code and formulas from Roark's Formulas for Stress and Strain are used to determine stacking limit for each type of linepipes. Stability analysis is governed by DNVGL-ST-N001 as an international standard to decide if pipe stacking attempt are according to stability criteria and find its stability properties. Sea fastening analysis is done using motion criteria from DNVGL-ST-N001.

2. MATERIALS AND METHODOLOGY

The following steps and procedures are conducted for this research. Firstly, a literature study is performed on materials regarding marine operations, particularly about marine transport and sea fastening operations, by researching international code, rules, and standards related to linepipe transportation. Other materials regarding stress and stability formulas are also considered for pipe stacking and stability calculations. Software used to help analyze optimization parameters are also studied and obtained, which are AutoCAD for drawings, Maxsurf for cargo barge modelling and stability analysis, and SACS for sea fastening analyses.

2.1 Data Collection

Data regarding this research are collected from Double Joint Linepipe Transportation for Tangguh Expansion Project by Saipem Indonesia, which are:

- Linepipe types and properties
- Environmental data
- Cargo barge specification
- Sea fastening property specifications

2.2 Pipe Stacking Analysis and Drawing

Pipe stacking analysis is conducted to determine the stacking limit for each type of linepipes for different methods of pipe stacking. Table 1 showcases linepipe data analyzed in this research.

Table 1. Linepipe data

Length	24.4 m		
SMYS	450 N/mm^2		
Type	Outer Diameter	Wall Thickness	Concrete Weight Coating
P2	610 mm	17.5 mm	30 mm
P3	610 mm	17.5 mm	40 mm
P4	610 mm	17.5 mm	80 mm
P5	616.2 mm	20.6 mm	80 mm
P6	610 mm	17.5 mm	115 mm
P7	616.2 mm	20.6 mm	115 mm

Pipe stacking methods included in this research are standard pipe stacking done by Saipem Indonesia and two alternate pipe stacking methods which are pipe stacking with side support and vertical pipe stacking. Pipe stacking analysis was conducted with guides from API RP 5LW and formulas from Roark's Formulas for Stress and Strain [2] to calculate total stress and load during pipe stacking. Parameters considered as stacking limit criteria and also as optimization parameters include:

- Steel stress
- Coating compressive strength between pipe and cargo barge
- Coating compressive strength between pipes
- Pipe stacking total load to the barge deck

Pipe stacking analysis results are stacking limit of each type of linepipe for both alternative methods which then used as a consideration when drawing alternative pipe stacking method layout using AutoCAD software.

2.3 Cargo Barge Modelling Stability Analysis

Cargo barge is modelled based on specifications from Saipem Indonesia, as shown in Table 2. Using Maxsurf software, cargo barge was modelled and validated based on its original stability booklet. Using guidance from ABS [4], the hydrostatic properties of the cargo barge model are compared to its original hydrostatic properties, which are displacement and both transverse and longitudinal length from keel to metacenter.

Table 2. Cargo barge data

Barge	
Name	Maritime East
LOA	85.95 m
Breadth	27.43 m
Depth	5.49 m
Draft	3.8 m
Deck Strength	10 T/m^2
Height Limit	4 m

Based on pipe stacking analysis and drawing, the total load of pipe stacking layouts are mapped to load cases which then used as input for stability analysis according to stability criteria from DNVGL-ST-N001. The parameters considered as stability criteria for optimization are:

- Initial metacentric height (GM)
- Intact stability range
- Maximum righting arm (GZ)

2.4 Sea fastening Modelling and Analysis

Based on linepipe data, sea fastening property data, and pipe stacking layout drawings, sea fastening is modelled with SACS software. Sea fastening properties data are shown in Table 3. The model is then analyzed to find its Unity Check (UC) value using motion criteria from DNVGL-ST-N001 [2]. Motion criteria are based on environmental data, shown in
Table 4, which categorize this operation as weather restricted on benign areas with L/B ratio of 1.4. Based on that category, motion criteria for sea fastening analysis are as stated in Table 5.

Table 3. Sea fastening properties data

SLING	
Type	6x37 IWRC Ø19 mm
PADEYE	
Density	7.849 T/m^3
Elasticity Modulus	200.000 MPa
Poisson's Ratio	0.3
Yield Strength	235 Mpa
Tensile Strength	483 Mpa

Table 4. Environmental data

Wind Speed	15.33 m/s
Current Speed	3 knot
Wave Height	3.6 m
Wave Period	10.4 s

Table 5. Motion criteria for linepipe transportation operation

Criteria	Value
Period (s)	10
Roll (°)	5
Pitch (°)	2.5
Heave	0.2 g

2.5 Optimization

Results from various analyses are gathered as optimization parameters to determine the most optimal pipe stacking method for linepipe transportation operation. Optimization is carried out using multi-criteria optimization, which defines utility function for each parameter which are.

- Linepipe qualities:
  - Steel stress
  - Coating compressive strength between linepipe and cargo barge deck
  - Coating compressive strength between linepipes
  - Pipe stacking total load to the barge deck
- Cargo barge stability:
  - Initial metacentric height (GM)
  - Intact stability range
  - Maximum righting arm (GZ)
- Sea fastening property strength

Variable changed during the optimization process is pipe stacking layout on cargo barge to maximize cargo barge deck capacity and minimize times of deliveries.

3. RESULT AND DISCUSSION

3.1 Pipe Stacking Analysis

Pipe stacking analysis is conducted to every type of linepipe for each alternate method of pipe stacking. Using data from Double Joint Linepipe Transportation of Tangguh Expansion Project from Saipem Indonesia, each type of linepipe are analyzed to determine its stacking limit based on each parameter's limit which are:

- Maximum steel stress limit is 405 MPa
- Maximum compressive stress to concrete coating is 27 MPa
- Maximum stacking height is 4 m
- Maximum load to the deck is 10 T/m^2

The result of pipe stacking analysis for pipe stacking with side support method is shown in Table 6 and for the vertical pipe stacking method results are shown in Table 7.

Table 6. Stacking limit of pipe stacking analysis for side support stacking method

Type	Stacking Limit	Critical Criteria	Value
P2	6	Maximum Height	3.63 m
P3	6	Maximum Height	3.74 m
P4	4	Maximum Steel Stress	346.23 MPa
P5	5	Maximum Load to Barge	9.58 T/m^2
P6	3	Maximum Steel Stress	323.71 MPa
P7	4	Maximum Load to Barge	9.22 T/m^2

Table 7. Stacking limit of pipe stacking analysis vertical stacking method

Type	Stacking Limit	Criteria	Critical Limit
P2	4	Maximum Compressive Strength on Coating Between Linepipes	22.82 MPa
P3	4	Maximum Compressive Strength on Coating Between Linepipes	22.39 MPa
P4	4	Maximum Compressive Strength on Coating Between Linepipes	22.51 MPa
P5	5	Maximum Compressive Strength on Coating Between Linepipes	23.42 MPa
P6	4	Maximum Steel Stress	399.83 MPa
P7	5	Maximum Load to Barge	9.46 T/m^2

Using stacking limit from each type of linepipes and methods, additional pipe stacking analysis is executed using guides and formulas from API RP 5LW [1], which calculates steel stress and compare it to SMYS. This analysis is done to satisfy international standard criteria and the result will not affect the optimization process which is shown in Table 8 and Table 9 for side support pipe stacking method and vertical pipe stacking method respectively.

Table 8. Pipe stacking Analysis Based on API RP 5LW for pipe stacking with the side support method

Pipe ID	OD (inch)	WT (ft)	σs (Psi)	Status
P2	24.02	0.06	41361.57	OK
P3	24.02	0.06	41361.57	OK
P4	24.02	0.06	27574.38	OK
P5	24.26	0.07	29879.29	OK
P6	24.02	0.06	20680.78	OK
P7	24.26	0.07	23903.43	OK

Table 9. Pipe stacking analysis based on API RP 5LW for vertical pipe stacking method

Pipe ID	OD (inch)	WT (ft)	σs (Psi)	Status
P2	24.02	0.06	27574.38	OK
P3	24.02	0.06	27574.38	OK
P4	24.02	0.06	27574.38	OK
P5	24.26	0.07	29879.29	OK
P6	24.02	0.06	27574.38	OK
P7	24.26	0.07	29879.29	OK

Alternative pipe stacking methods are drawn using AutoCAD, both from the front and top view. Figure 1 and Figure 2 shows an example of AutoCAD drawing of linepipe layout on the cargo barge.

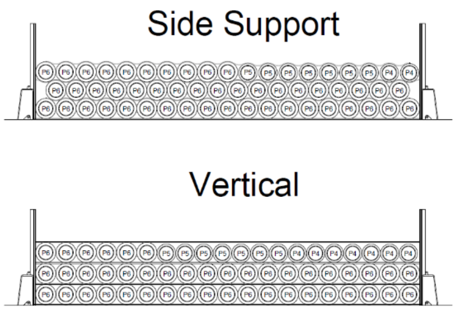

Figure 1. Front view example of pipe stacking layout on the cargo barge

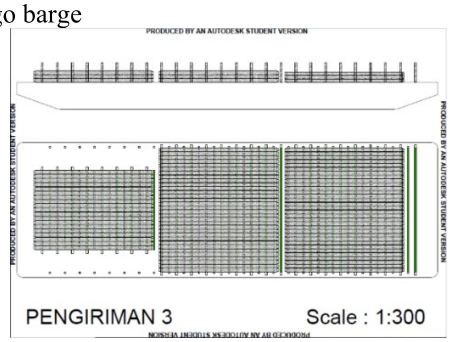

Figure 2. Top view example of pipe stacking layout on the cargo barge

3.2 Cargo Barge Modelling and Stability Analysis

Cargo barge used in transport operation is then modelled and analyzed which the result then used as one of the optimization parameters. Cargo barge used in the analysis is modelled using Maxsurf software. Next, the cargo barge model is validated to its stability booklet specifications. Hydrostatic properties used in the validation process are displacement and transversal & longitudinal distance of Keel to Metacenter (KM). For displacement, the validation tolerance to not exceed 2% and both transversal and longitudinal KM to not exceed 1%. Table 10 shows the validation result.

Table 10. Validation of cargo barge model

Draft	Property	Booklet	Maxsurf	Tolerance	Status
3.8	Δ (ton)	8182.97	8195	0.15%	OK
	KMt (m)	20.49	20.48	0.04%	OK
	KMl (m)	183.85	183.524	0.18%	OK
5.2	Δ (ton)	11567.25	11579	0.10%	OK
	KMt (m)	15.82	15.81	0.04%	OK
	KMl (m)	131.45	131.21	0.18%	OK

After the model was validated to be used in stability analysis, water ballast tanks are defined in room definition section filled to 2% capacity like Linepipe Transport Operation by Saipem Indonesia. After that, load cases are defined by using the total load of each batch of alternative pipe stacking methods. Load cases for alternate methods are shown in Table 11.

Table 11. Load cases for both alternative pipe stacking method

Batch	Rack	Side Support (Ton)	Vertical (Ton)
1	1	1886.71	1997.33
	2	1649.07	1762.22
	3	2221.1	1997.33
2	1	2324.07	2351.1
	2	1598.54	1567.4
	3	2324.07	2328.19
3	1	1422.78	1463.6
	2	1979.41	1897.78
	3	2489.57	2530.38
4	1	1421.02	1862.72
	2	0	0
	3	1842.5	1400.8
5	1	1337.38	1306
	2	1938.6	1331.89
	3	1331.34	1969.42

These defined load cases are used as inputs for stability analysis. Stability analysis is done according to stability criteria from DNVGL-ST-N001 and the results are shown in Table 12. Stability criteria from DNVGL-ST-N001 [2] include:

- Initial GM to exceed 0.15 m
- Intact stability ranges to exceed 36°

Table 12. Stability Analysis Results

Method	Batch	GZ (m)	GZ at 36°	*Initial* GM
Side Support	1	2.403	0.651	13.026
	2	1.981	0.262	12.108
	3	2.185	0.396	12.633
	4	4.441	2.393	19.554
	5	3.379	1.537	15.719
Vertical	1	2.385	0.639	13.052
	2	1.969	0.236	12.070
	3	2.164	0.348	12.552
	4	4.292	2.255	19.550
	5	3.376	1.537	15.701

3.3 Sea fastening Modelling and Analyses

Sea fastening analysis and modelling are conducted using SACS software based on motion criteria of DNVGL-ST-N001 [2]. Sefastening model is generated for racks with the highest load of every pipe stacking method. Sea fastening properties analyzed include padeye and sling. UC value is then used as one of the optimization parameters. UC values from sea fastening analyses are included in Table 13.

Table 13. Sea fastening Analysis Results for Alternative Pipe stacking Method

Group	Max UC	
	Side Support	Vertical
P4	0.01	0.01
PAD	0.06	0.001
WRP	0.13	0.14

3.4 Optimization

Optimization using multi-criteria method is done by defining utility functions for each optimization parameters [1]. The goal of optimization is to find the most optimal method of pipe stacking while minimizing the number of deliveries and maximizing barge rack capacity. Variables changed in optimization is pipe stacking method layout. Limitations which are also used as comparison parameters are linepipe qualities, cargo barge strength and stability, and sea fastening property strength. The first attempt of optimization is to reduce the number of delivery into 4 batches. The result of the first iteration of optimization is presented in Table 14 and Table 15.

Table 14. Pipe stacking analysis result for the first iteration of the optimization

Method	Steel Stress (Mpa)	Coating Stress (MPa)		Height (m)	Load (T/m^2)
		Barge	Linepipe		
Vertical	399.83	12.47	23.38	3.51	7.20
Side Support	438.93	15.10	5.96	3.01	7.89
Standard	358.65	13.18	8.09	3.49	9.46

Table 15. Stability and sea fastening analysis for the first iteration of optimization

Method	Barge Stability			Sea fastening Max UC
	Min. GZ Value At 36^0 (m)	Initial GM (m)	Max GZ (m)	
Vertical	-0.53	11.69	1.87	0.22
Side Support	-0.27	12.72	2.29	0.13
Standard	-0.12	11.89	1.97	0.14

According to stability criteria from DNVGL-ST-N001, the first iteration optimization failed one of its stability analysis criteria, because there are intact ranges less than 36°. The second iteration of optimization while also delivers 5 times, same as originally done by Saipem Indonesia, the pipe stacking layout are different to maximize cargo barge capacity while balancing its load over 5 deliveries. Standard stacking, stacking with side support, and vertical stacking methods are used. Pipe stacking parameters results for all stacking method are presented in Table 16 and stability and sea fastening properties are presented in Table 17.

Table 16. Pipe stacking analysis result for the second iteration of optimization

Method	Steel Stress (Mpa)	Coating Stress (MPa)		Height (m)	Load (T/m^2)
		Barge	Linepipe		
Vertical	301.92	14.46	23.60	3.23	6.00
Side Support	319.60	16.80	5.97	2.82	6.37
Standard	284.09	14.65	7.50	2.82	6.00

Table 17. Stability and sea fastening analysis for second iteration of optimization

Method	Batch	Barge Stability			Sea fastening Max UC
		GZ at 36^0 (m)	Initial GM (m)	Max GZ (m)	
Vertical	1	1.19	14.54	2.95	0.14
	2	1.12	14.37	2.90	
	3	0.98	14.01	2.76	
	4	0.88	13.95	2.76	
	5	1.34	15.00	3.12	
Side Support	1	1.14	14.39	2.89	0.14
	2	1.13	14.35	2.87	
	3	1.78	18.24	4.07	
	4	0.99	14.21	2.86	
	5	1.78	18.24	4.17	
Standard	1	1.26	14.78	3.03	0.13
	2	1.17	14.47	2.92	
	3	0.93	13.83	2.71	
	4	1.14	14.44	2.92	
	5	0.96	13.94	2.73	

The next step of optimization is to define utility function for every parameter. Definition of every parameter's utility function is as follow:

- Linepipe qualities parameter
  Categorized as lower better, pipe stacking parameters include steel stress, concrete coating strength, stack height, and load to barge. Maximum value is used in optimization utility calculation which is defined as:
  $$U(f) = 1 - \frac{f}{f_{limit}} \quad (1)$$
  Where $\boldsymbol{f}$ is parameter value and $\boldsymbol{f_{limit}}$ is maximum parameter limit
- Stability parameters
  Categorized as higher, stability parameters include initial GM, intact stability range, and GZ. The average value is used in optimization utility calculation which is defined as:
  $$U(f) = \frac{f}{f_{max}} \quad (2)$$
  Where $\boldsymbol{f_{max}}$ is maximum parameter value.
- Sea fastening parameter
  Categorized as higher better and maximum value is used in optimization utility calculation which is defined as:
  $$U(f) = 1 - f \quad (3)$$

The next step is to weight utility functions and define aggregate utility function which is used to get optimization value for every method that is proposed. The weight of every parameter are equally divided and aggregate utility function is defined as follow:

$$Weight\ for\ every\ parameter\ (w) = \frac{100\ \%}{9} = 11.11\ \%$$

$$U_{total} = U_1 \times w + U_2 \times w + U_3 \times w \ldots + U_9 \times w$$
$$= (U_1 + U_2 + U_3 + U_4 + U_5 + U_6 + U_7 + U_8 + U_9) \times w$$

U_{total} = Total utility function
U_1 = Steel stress utility function

U_2 = Concrete coating stress between linepipe and cargo barge utility function
U_3 = Concrete coating stress between linepipes function
U_4 = Stack height utility function
U_5 = Cargo barge strength utility function
U_6 = GZ value at 36° utility function
U_7 = Initial GM utility function
U_8 = Maximum GZ utility function
U_9 = Sea fastening UC utility function

Table 18. Optimization value of all pipe stacking attempt

U(f)	Vertical	Side Support	Standard	SAIPEM
Steel stress (Mpa)	0.25452	0.21087	0.29855	0.114
Coating Stress to Barge (Mpa)	0.46438	0.37786	0.45724	0.374
Coating Stress to Linepipe (Mpa)	0.1261	0.77903	0.72209	0.686
Height (m)	0.1936	0.29536	0.29536	0.127
Load to Barge (T/m2)	0.40012	0.36263	0.40012	0.25
GZ at 36^0 (m)	0.80763	1	0.79956	0.852
Initial GM (m)	0.90478	1	0.89967	0.906
Max GZ (m)	0.85968	1	0.84877	0.95
UC	0.14	0.14	0.13	0.15
$\sum$	4.15082	5.16575	4.85136	4.409
w	11.1111	11.1111	11.1111	11.1111
U	46.1202	57.3972	53.904	48.99

4. CONCLUSIONS

A study regarding pipe stacking method optimization for the case of linepipe transport operation has been concluded. The result of this study can be described as follow:

- Pipe stacking analysis results for alternative methods can be found in Table 21 and Table 22. Sea fastening analysis results for alternative methods are 0.13 for side support stacking and 0.14 for vertical stacking in Unity Check.

Table 19. Pipe stacking result for using side support method

Type	Stacking Limit	Critical Criteria
P2	6	Maximum Height
P3	6	Maximum Height
P4	4	Maximum Steel Stress
P5	5	Maximum Load to Barge
P6	3	Maximum Steel Stress
P7	4	Maximum Load to Barge

Table 20. Pipe stacking result for using vertical stack method

Type	Stacking Limit	Critical Criteria
P2	4	Maximum Compressive Strength on Coating Between Linepipes
P3	4	Maximum Compressive Strength on Coating Between Linepipes
P4	4	Maximum Compressive Strength on Coating Between Linepipes
P5	5	Maximum Compressive Strength on Coating Between Linepipes
P6	4	Maximum Steel Stress
P7	5	Maximum Load to Barge

- Alternative pipe stacking method generates more stress and load while scoring less stability and sea fastening strength.
- Optimization resulted pipe stacking with side support method which was 8.41% more optimized than pipe stacking method by Saipem Indonesia.

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