Technical Review of Bollard Pull Calculation to Support Shuttle Tanker from Spread Mooring System FSO

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Abstract. An FSO was designed with Spread Mooring System to substitute the former FSO whose mooring system was designed with Turret Mooring System. Theoretically, the environmental loads affecting the shuttle tanker when the crude oil transfer process from FSO is undergone, it will have a bigger number and require a bigger bollard pull specification of the AHTS vessels to assist the shuttle tanker in place. It is due to the weathervane flexibility that is adjusted to the heading direction of either the FSO or shuttle tanker which found in Turret Mooring System is absent in Spread Mooring System. The calculation of environmental loads in this research is conducted using recommendation from DNV-GL and wind, wave, current, and inertia loads are taken into accounts. The biggest transversal environmental load is recorded by the magnitude of 262.96 MT towards positive vector. Whilst the biggest longitudinal environmental load is recorded by the magnitude of 105.44 MT towards negative vectors. By considering safety factor, age, efficiency, and towing configuration of the AHTS vessels, the recommended specification of the AHTS vessels configuration are the 200 MT AHTS vessel in stern of the shuttle tanker and 220 MT AHTS vessel in port side or starboard side of the shuttle tanker.

1. Introduction
The use of fossil fuels is still very important in our daily life. The statistical data published by PwC Indonesia proofed that the demand of fossil fuels in Indonesia is increasing rapidly every year, yet it is contradicted with the depleting of productivity in existing onshore oil fields [1]. It pushes the government to start exploring oil fields in unconventional and marginal areas, for example the offshore oil fields.

In order to support the day-to-day operations in offshore oil fields whose characteristic is critically isolated, therefore we need highly reliable offshore facilities. One of the offshore facilities that often used is Floating Storage and Offloading (FSO). FSO is a ship shaped floating facility that is moored to keep it static to contain the crude oil obtained from surrounding oil wells via subsea risers [2].

This paper studied about a FSO that will be moored with a Spread Mooring System (SMS) configuration that has been operating since 2018 to substitute the former FSO whose mooring configuration used was the Turret Mooring System. A turret mooring system is an example of a single point mooring that sometimes can be unstable in terms of yaw motions [3]. While the SMS configuration is considered can be operated in all weather conditions and also can have a long lifetime [4]. A
replacement of FSO in the middle of production phase has rarely been done and remains novel until now. The complexity of the procedure is the sole reason engineers have chosen other options such as modifying the FSO rather than substituting it. The weather versatility, which is also found in the dynamic positioning system [5], is an issue in the former FSO with Turret Mooring System to adjust its position around the fixed geostatic part of the turret was vanished as the result of changing the FSO with SMS mooring configuration. The static condition of current FSO would lead to higher environmental loads received by the shuttle tanker when undergo crude oil transfer.

The AHTS vessels towing configuration that is not replaced whilst applying the different mooring configuration of FSO will lead to future problems. The lower specification of AHTS vessels being used will be insufficient to assist shuttle tanker when undergoing crude oil transfers from Spread Mooring System FSO and crude oil transfer has to be done in a strict operational window. The company report shows that crude oil transfer was postponed and aborted for multiple times in the last six months, not to mention the near miss accident. Therefore, reanalyzing the environmental loads received by the shuttle tanker when undergoing a crude oil transfer from the FSO is a step that should be taken to assure the safety of crude oil transfer operation and reviewing the AHTS vessels towing configuration.

This objective of this paper is to design a new AHTS vessels configuration to support shuttle tanker from FSO in crude oil transfer that can meet the requirement from calculated bollard pull in accordance with DNV-GL regulations.

2. Methodology

The environmental loads that are taken into consideration on this research are wind, wave, current, and inertia load. The load calculation uses a static hydrodynamic approach based on the environmental load recommendations from DNV-GL.

There are several methods and formulas to calculate wind load and current load, yet the OCIMF (Oil Companies International Marine Forum) formulas is used as recommended by DNV-GL [5]. The formula from the Spanish Standard ROM 0.2-90 is used to calculate the wave load. And last, formula by Chakrabarti is used to calculate inertia load on this research [6].

2.1. Data Collection

The research needs supporting data that can assist the process to complete the research. The obtained data will be processed later to be used as a reference for evaluating the existing AHTS vessels configuration to assist the shuttle tanker from Spread Mooring System FSO. The supporting data includes Metocean Data, AHTS vessels specifications, and shuttle tankers principal dimensions.

The shuttle tanker data being used in this research is obtained by selecting the biggest principal dimension from shuttle tankers that has ever done crude oil transfer from the FSO in the last six months. The selected shuttle tanker is MT Mare Oriens with specification as shown in Table 1.

2.2. Evaluation of Existing Configuration

According to DNV-OS-H202 Section 4: Towing, the value of effective bollard pull of AHTS vessels will decrease every year [5]. The reduction rate of effective bollard pull is 10% + 2% per year from the latest documented bollard pull [7]. Therefore, towing configuration is firstly being evaluated to obtain the actual value of bollard pull on each AHTS vessel.

2.3. Environmental Loads Calculation

Environmental loads are calculated to be the basis of calculating the required bollard pull. The load calculation process uses the calculation steps recommended by DNV-GL [8] [9] and [10] with formulas obtained from OCIMF, the Spanish Standard ROM 0.2-90, and Chakrabarti. It is divided in two conditions, the first one is when shuttle tanker is in connecting process to the FSO, and second is when shuttle tanker is already connected to the FSO.
Table 1. Principal Dimension of MT Mare Oriens

| Name          | MT Mare Oriens |
|---------------|----------------|
| Type          | Oil tanker     |
| Year of build | 2008           |
| Class register| RINA           |
| Flag          | Italy          |
| IMO           | 93468773       |
| Call sign     | ICDY/247254100 |
| Gross tonnage (GT) | 59,611          |
| Deadweight tonnage (DWT) | 113,179 ton    |
| Length overall (LOA) | 245.55 m       |
| Length between perpendicular (LPP) | 235.72 m      |
| Breadth (B)   | 42.01 m        |
| Height (H)    | 21.51 m        |
| Freeboard (full) | 6.58 m         |
| Freeboard (ballast) | 14.68 m       |
| Draught (full) | 14.98 m        |
| Draught (ballast) | 6.89 m         |
| Speed         | 16 knots       |

Transversal wind load:

\[ F_{YC} = \frac{C_{YC} \times YC \times D \times LPP \times V_C^2}{20000} \] (1)

Longitudinal wind load:

\[ F_{XW} = C_{XW} \times \rho \times A_L \times \frac{V_{WP}^2}{20000} \] (2)

Transversal wave load:

\[ F_{Y \text{wave}} = C_{fw} \times C_{dw} \times \gamma_{dw} \times H_s^2 \times D' \times \sin \alpha \] (3)

Longitudinal wave load:

\[ F_{X \text{wave}} = C_{fw} \times C_{dw} \times \gamma_{dw} \times H_s^2 \times D' \times \cos \alpha \] (4)

Transversal current load:

\[ F_{YC} = \frac{C_{YC} \times YC \times D \times LPP \times V_C^2}{20000} \] (5)

Longitudinal current load:

\[ F_{XC} = \frac{C_{XC} \times YC \times B \times LPP \times V_C^2}{20000} \] (6)

Transversal inertia load:

\[ F_{VR} = \left[ \frac{4 \pi^2 \theta_X + (1 \pm 0.2) \cos \theta}{T \times 1000} \right] g \times 100 \] (7)

Longitudinal inertia load:

\[ F_{HR} = \left[ \frac{4 \pi^2 \theta_Z + (1 \pm 0.2) \sin \theta}{T \times 1000} \right] g \times 100 \] (8)
2.4. Bollard Pull Calculation

Bollard pull calculation should be performed to know the minimum specification of AHTS vessels to support shuttle tanker from the FSO. Bollard pull calculation is calculated using formula and recommendation from DNV-GL. The bollard pull calculation formula is as follows.

\[ Y_{TE} = \frac{80-(18-(0.0417 \times \text{LOA} \times \sqrt{\text{BP}} - 20)) \times (H_s - 1)}{100} \]  \hspace{1cm} (9)

2.5. Bollard Pull Calculation

Data verifying is performed to review whether the existing configuration is sufficient to assist shuttle tanker from the FSO in crude oil transfer. If existing configuration is insufficient, re-establishing a new configuration according to the result of this research should be done.

3. Result and Discussion

3.1. General Information

General information is served to ease the readers depicting the condition in the field. Figure 1 shows the weather direction that used in this research. The angle interval is 45 with 0° comes from bow of shuttle tanker. The X-positive axis towards starboard side of shuttle tanker and Y-positive axis towards the stern side of shuttle tanker.

![Figure 1. Weather direction](image)

3.2. Actual Bollard Pull Calculation of Existing Configuration

The actual output of bollard pull from AHTS vessels will be reduced in accordance with its age. The reduction factor according to DNV-OS-H202 is 2% per year from the latest documented bollard pull [5]. The equation of actual bollard pull is shown as follows.

\[ BP_{rull} = BP_c - (F_R \times BP_c \times n) \]  \hspace{1cm} (10)

By using the equation (10), the value of actual bollard pull of each existing AHTS vessel can be acquired. Table 2 shows the actual bollard pull that has been reduced in accordance with its age using recommendation from DNV-GL.

From Table 2, it can be seen that the bollard pull of Catherine Queen is reduced with value of 10.2 MT and SMS Steady is reduced with value of 4.8 MT from what stated in the bollard pull certificates.

| Name           | Initial bollard pull (T) | Year of built n | Reduction factor | Existing bollard pull (T) |
|----------------|--------------------------|-----------------|------------------|---------------------------|
| Catherine Queen| 85                       | 2014            | 6                | 74.8                      |
| SMS Steady     | 48                       | 2015            | 5                | 43.2                      |
3.3. Defining Operations Window

The values of actual bollard pull in Table 2 will later be used as a reference to verify the sufficiency of existing configuration based on calculated environmental loads in this research. Due to the operation of crude oil transfer from the FSO lasts less than 72 hours, according to DNV-OS-H101: Marine Operations, General, the marine operation may normally be defined as weather restricted [7]. Weather restricted means that the environmental loads shall be calculated with defined design weather characteristic. The weather characteristic in this paper uses strong breeze characteristic according to Beaufort Scale. The design of operation window can be seen on Table 3.

| Table 3. Operation window based on the weather condition |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Parameter       | 0°              | 45°             | 90°             | 135°            | 180°            | 225°            | 270°            | 315°            |
| Hs (m)          | 3               | 3               | 3               | 3               | 3               | 3               | 3               | 3               |
| Wind (m/s)      | 13              | 13              | 13              | 13              | 13              | 13              | 13              | 13              |
| Current(m/s)    | 1               | 1               | 1               | 1               | 1               | 1               | 1               | 1               |
| Water Depth (m) |                 |                 |                 |                 |                 |                 |                 | 77              |

3.4. Environmental Loads Calculation

This research divided the calculation of environmental loads into two conditions, when shuttle tanker is already connected to the FSO (loaded condition) and when shuttle tanker is in connecting process to the FSO (ballasted condition).

3.4.1. Loaded Condition. Figure 2a. shows the result of transversal environmental loads on loaded condition in all-weather direction from 0° to 315° with interval 45°. The peak of wind load is recorded in weather direction comes from 90° with value -16.78 MT, wave load in weather direction comes from 270° with value 128.62 MT, and current load in weather direction comes from 90° and 270° with value -117.63 MT and 117.63 MT respectively.

Figure 2b. shows the result of longitudinal environmental loads on loaded condition in all-weather direction from 0° to 315° with interval 45°. The peak of wind load is recorded in weather direction comes from 0° with value 9.99 MT, wave load in weather direction comes from 225° with value -80.10 MT, and current load in weather direction comes from 0° and 180° with value 17.76 MT and -17.76 MT respectively.

3.4.2. Ballasted Condition. Figure 3a. shows the result of transversal environmental loads on ballasted condition in all-weather direction from 0° to 315° with interval 45°. The peak of wind load is recorded in weather direction comes from 270° with value 84.23 MT, wave load in weather direction comes from
270° with value 26.41 MT, current load in weather direction comes from 90° and 270° with value -40.79 MT and 40.79 MT respectively, and inertia load 10.59 MT.

Figure 3b. shows the result of longitudinal environmental loads on ballasted condition in all-weather direction from 0° to 315° with interval 45°. The peak of wind load is recorded in weather direction comes from 0° with value 11.83 MT, wave load in weather direction comes from 225° with value -25.84 MT, current load in weather direction comes from 0° with value 26.90 MT, and inertia load with value 3.33 MT.

3.5. Worst Case Scenario

After calculating environmental loads on all weather direction in two shuttle tanker conditions, the next step taken is to choose the weather criteria to be the basis of bollard pull calculation. The choosing of weather criteria options are looking at the worst possible scenario when the biggest wind, wave, and current load occurs in one axis. This step is taken to assure that the recommended operations of crude oil transfer can be overcame when worst weather occurs under the operations window. This research also takes the three biggest resultants of environmental loads into consideration.

Table 4 shows two worst cases of scenarios when the biggest total environmental loads occur under the same axis. Case 1 shows when the biggest total transversal load occurs. The biggest total transversal load occurs when wind, wave, and current load all come from 270°. Case 2 shows the biggest total longitudinal load occurs. The biggest total longitudinal load occurs when current comes from 225° and wind and current both come from 180°.

Table 5 shows three worst case scenarios when the biggest resultant of environmental loads occurs. Case 3 is when wind comes from 180° and both wave and current come from 270°. Case 4 is when all wind, wave, and current all come from 90°. Case 5 is when wind comes from 135° and both wave and current come from 90°.

| Variable | Case 1 | Case 2 |
|----------|--------|--------|
|          | Value  | Direction | Value  | Direction |
| Fy       |        |           |        |           |
| $F_{\text{wind}}$ | 16.72 MT | 270° | 0.00 MT | 180° |
| $F_{\text{wave}}$ | 128.62 MT | 270° | 80.10 MT | 225° |
| $F_{\text{current}}$ | 117.63 MT | 270° | 0.00 MT | 180° |
| $F_{\text{YT}}$ | 262.96 MT | 270° | 80.10 MT | 180° |
| Fx       |        |           |        |           |
| $F_{\text{wind}}$ | -0.33 MT | 270° | -7.58 MT | 180° |
| $F_{\text{wave}}$ | 0.00 MT | 270° | -80.10 MT | 225° |
| $F_{\text{current}}$ | -3.30 MT | 270° | -17.76 MT | 180° |
| $F_{\text{XT}}$ | -3.63 MT | 270° | -105.44 MT | 180° |
Table 5. Resultants of Environmental Loads in Worst Case Scenario

| Variable | Case 3 | Case 4 | Case 5 |
|----------|--------|--------|--------|
|          | Value  | Direction | Value  | Direction | Value  | Direction |
| Fwind    | 0.00 MT | 180°    | -16.78 MT | 90°      | -13.61 MT | 135°     |
| Fwave    | 128.62 MT | 270°    | -104.10 MT | 90°      | -104.10 MT | 90°      |
| Fcurrent | 117.63 MT | 270°    | -117.63 MT | 90°      | -117.63 MT | 90°      |
| FYT      | 246.25 MT |         | -238.51 MT |         | -235.34 MT |          |
| Fwind    | -7.58 MT | 180°    | -0.33 MT | 90°      | -4.66 MT | 135°     |
| Fwave    | 0.00 MT | 270°    | 0.00 MT | 90°      | 0.00 MT | 90°      |
| Fcurrent | -3.3 MT | 270°    | -3.30 MT | 90°      | -3.30 MT | 90°      |
| FXT      | -10.88 MT |         | -3.63 MT |         | -7.96 MT |          |
| Fr       | 246.49 MT | 45°     | 238.54 MT | 45°      | 235.46 MT | 45°      |

The new configuration is designed under consideration of all five worst case scenarios. Figure 4 shows new recommended configuration with AHTS vessel A is placed in stern of shuttle tanker to counteract transversal and longitudinal load and AHTS vessel B is placed in port side or starboard side of shuttle tanker to counteract merely transversal load. The manoeuvring angle of AHTS vessel A is designed with maximum angle of 60°. The designed safety factor to calculate the required bollard pull is determined with value of 1.2.

![Figure 4. New Configuration](image)

Table 6 shows the specification of AHTS vessels that are available in market in new configuration. \( BP_{spec} \) is the bollard pull of AHTS vessel according to what stated in certificate. \( BP_{reel} \) is the bollard pull of AHTS vessel after getting reduced with towing efficiency according to DNV-GL recommendation. \( Fx \) is the bollard pull output of AHTS vessel in x axis to counteract longitudinal environmental loads. \( Fy \) is the bollard pull output of AHTS vessel in y axis to counteract transversal environmental loads.

Data verification is needed to validate whether the existing and new configuration is sufficient to assist shuttle tanker. Existing condition is compared with new condition to verify with requirement under five worst scenarios.

Table 7 shows whether existing condition and new scenario are sufficient to support shuttle tanker under five worst case scenarios. Requirement column indicates the required minimum bollard pull after getting multiplied with safety factor. It can be seen from Table 7 that existing condition with Catherine Queen and SMS Steady is insufficient to support tanker in designed operation window. Contradict to
the existing condition, new condition with 200 MT and 220 MT AHTS vessels is sufficient to support shuttle tanker in all five worst scenarios.

**Table 6. Resultants of Environmental Loads in Worst Case Scenario**

| Variable | AHTS A | AHTS B | Unit |
|----------|--------|--------|------|
| BP<sub>spec</sub> | 200 | 220 | MT |
| BP<sub>nil</sub> | 164.28 | 180.71 | MT |
| M/E | 4 x 3060 | 2 x 4000 | kW |
| | 2 x 3000 | | kW |
| LOA | 89.1 | 85.2 | M |
| B | 22 | 22 | M |
| T | 7 | 7.6 | M |
| Speed | 16.4 | 17 | Knots |
| DWT | 3700 | 4500 | MT |
| Fx | 82.14 | 0.00 | MT |
| Fy | 142.27 | 180.71 | MT |

**Table 7. Verification of New and Existing Condition**

| Case | Requirement | Existing Condition | New Scenario | Unit |
|------|-------------|--------------------|--------------|------|
|      | Fy | Fx | Fy | Fx | Fy | Fx | Fy | Fx |
| Case 1 | 315.55 | 4.36 | 88.69 | 30.72 | 322.98 | 82.14 | MT |
| Case 2 | 96.12 | 126.53 | 35.48 | 61.44 | 180.71 | 164.28 | MT |
| Case 3 | 246.69 | 80.18 | 255.56 | MT |
| Case 4 | 238.54 | 80.18 | 255.56 | MT |
| Case 5 | 235.46 | 80.18 | 255.56 | MT |

**4. Conclusion**

Based on the result of environmental loads and bollard pull calculation in this research, the following conclusions are obtained:

1) According to environmental loads calculation in worst case scenario under weather restricted operations, the recorded biggest transversal load is 262.96 MT with all weather directions from 270°. And for the biggest longitudinal load is -105.44 MT with weather directions from 180° and 225°.

2) The bollard pull calculation indicates that the existing condition with Catherine Queen and SMS Steady is insufficient to support shuttle tanker from the FSO under designed operations window. Thus, a new scenario is established with 200 and 220 MT AHTS vessels.

3) The new recommended towing configuration in this research is 200 MT AHTS vessel in stern of shuttle tanker to counteract transversal and longitudinal load and 220 MT AHTS vessel in port side or starboard side of shuttle tanker to counteract merely transversal load.

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