Stability Analysis of Offshore Wind Turbine Support Structure with Tension Leg Platform Type

Muhammad Alieviansyah Sumono[1], Gilang Muhammad Gemilang[2], Arianta Arianta[3]

{viansyahaliev@yahoo.com[1], gilang.mg@universitaspertamina.ac.id[2], arianta1@universitaspertamina.ac.id[3]}

Universitas Pertamina, Jakarta, Indonesia[1,2,3]

Abstract. TLP (Tension Leg Platform) which is an offshore floating structure for wind turbines has column and tendon configurations that vary depending on the construction site. This study examines the proper column and tendon configuration to support TLP wind turbines in Indonesia's offshore by comparing the 1 column and 4 columns TLP based on MIT TLP and Windstar TLP as well as comparing 1 tendon and 2 tendons TLP at each of the lower pontoon based on Rick Mercier's stability criteria. TLP stability analysis was analyzed using a frequency domain method and calculation of RAO (Response Amplitude Operator). The results indicate that the proper configuration of the TLP column and tendon as a wind turbine support structure is 4 columns configuration (Windstar TLP) with 2 tendons that have operating stability criteria and a stability value of 0,055° in the direction of pitch movement.

Keywords: TLP, MIT, Windstar, RAO, Stability

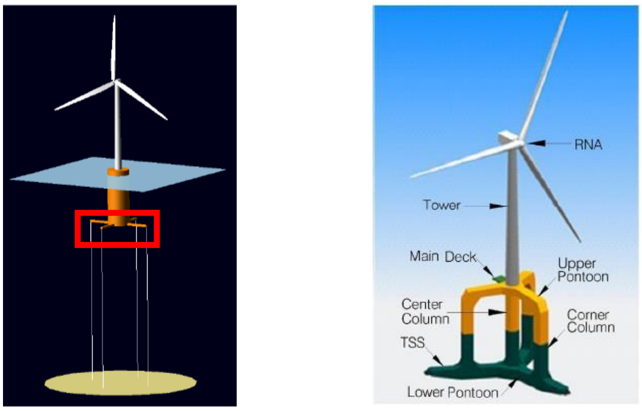
1 Introduction

The tension leg platform (TLP) is a floating structure tauted by prestressing using tendons. The advantage of TLP compared to other structures is that TLP does not require a large draft such as the Single Point Anchor Reservoir (SPAR) structure or does not require a spread mooring system such as a submersible structure to resist the structural loads of towers and wind turbine blades.[1] Besides that, TLP structures have a variety of column and tendon configurations used offshore. There are 2 types of TLP column configurations, namely mono-column TLP and multi-column TLP. Mono-column TLP is a TLP consisting of 1 column. Mono-column TLP research has been carried out by Matha named Massachusetts Institute of Technology (MIT) TLP and can be seen MIT TLP image in Figure 1(a).[1] The MIT TLP also has 4 horizontal lower pontoon structures connected at 4 points at the bottom of the column as shown in Figure 1.1(a) marked with a red square. Meanwhile, multi-column TLP is a TLP consisting of 2 or more columns where the addition of these columns can increase the difficulty in terms of TLP fabrication than MIT TLP. In addition, by having a more difficult

ICONIC-RS 2022, March 31-April 01, DKI Jakarta, Indonesia

DOI 10.4108/eai.31-3-2022.2320683

abrication, Windstar TLP required more time and money than MIT TLP to build the platform. The concept of multi-column TLP has been researched by Zhao, et al., named Windstar TLP with details of 1 center column and 3 corner columns.[2] The center and corner columns of Windstar TLP are connected by a horizontal upper pontoon structure at the top of the column and a horizontal lower pontoon structure at the bottom of the column as shown in Figure 1(b).



(a) (b)

Fig. 1. (a) Mono-Column TLP; (b) Multi-Column TLP [2,3]

Besides the column configuration, TLP has 2 types of tendon configurations. For example, the MIT TLP has a configuration of 2 tendons attached at each end of the lower horizontal pontoon. While the Windstar TLP has a configuration of 1 tendon that is attached to each end of the lower horizontal pontoon. According to Tabeshpour, et al., if the TLP loses one of the tendons, it will increase the static and dynamic stress on the remaining tendons.[2] In addition, according to Chatterjee, if the tendon prestress is too high then it will put the tendon at risk of failure in terms of structural strength or resistance to fatigue failures.[2] However, if the tension in the tendon is too low, the tendon will slack. From the explanation of the configuration of column and tendon that has been discussed, it can be said that a study is needed to determine the most suitable configuration of column and tendon for Indonesian offshore. The most suitable configuration type is determined by comparing the best stability between 1 column and 4 columns configuration as well as comparing the best stability between 1 tendon and tendons configuration. Besides that, MIT and Windstar TLP were chosen as representatives of 1 and 4 columns TLP because both structures are capable of supporting the National Renewable Energy Laboratory (NREL) 5 MW wind turbine from previous TLP studies. NREL 5 MW wind turbine specification can be found in Jonkman.[3]

Stability is important for offshore wind turbine support structures. With a stable support structure, the wind turbine can work optimally. According to Rick Mercier (2004), the stability criteria for offshore wind turbines to work can be seen from the magnitude of the direction of the pitch movement that occurs in the supporting structure of the offshore wind turbine [3]. Rick Mercier's stability criteria are divided into 4 categories, namely operating, survival, stand-by, and damaged. From four criteria, operating criteria is criteria where the wind turbine can operate. Survival criteria is a condition of stability one level above operating where the wind turbine can still work. Meanwhile, the standby and damaged stability criteria are the criteria for discontinuing the wind turbine operation. Thus, to achieve optimum stability, namely the operating stability criteria, it is necessary to analyze the stability of the wind turbine TLP. TLP stability analysis of the wind turbine was carried out in the Makassar Strait. The area was chosen because it has a large wind energy potential for power generation [3].

2 Methods

This study was conducted by modeling MIT and Windstar TLP based on the TLP specification data that had been collected. In modeling, TLP simulations were also carried out in Makassar Strait with environmental data which can be seen in tables 1 to 3.

Table 1. Ocean Current Speed Data in the Makassar Strait [9]

	10 Years	**100 Years**
Surface Current Speed (m/s)	1,11	1,31
Base Current Speed (m/s)	0,55	0,6

Table 2. Wind Speed Data in the Makassar Strait [9]

	0°	**45°**
10 Years Wind Speed (m/s)	17,4	15,3
100 Years Wind Speed (m/s)	21,2	18,7

Table 3. Ocean Wave Data in the Makassar Strait [9]

	0°	**45°**
10 Years		
Significant Wave Height (m)	2,2	1,8
Significant Wave Period (s)	7,1	6,5
100 Years		
Significant Wave Height (m)	3	2,5
Significant Wave Period (s)	8,3	7,6

Modeling specifications for MIT and Windstar TLP can also be seen in table 4. In addition, modeling results will be verified against displacement and center of buoyancy data of MIT and Windstar TLP specifications to ensure that the modeling carried out by Moses is suitable for further analysis. The next analysis is the calculation of the response spectrum. In this study, the response spectrum was calculated to obtain structural stability. Response Amplitude Operator (RAO) on the direction of pitch movement is used to calculate the response spectrum because according to Rick Mercier, the stability of the offshore wind turbine to work is sufficient in terms of the direction of the pitch motion. The frequency-domain method was used as method of calculating the response spectrum. The Frequency-domain method is a method that transforms wave spectrum into load spectrum that can act on the offshore structures. The response spectrum equation such as the equation below was used in this method [10].

$$S_R(\omega) = [RAO(\omega)]^2 S(\omega) \qquad (1)$$

The calculation of the response spectrum is carried out based on the tabulation process where the calculation process in the table will produce Σ0 which is the cumulative result of the sum of the rows of the response spectrum table. Σ0 result will be used to obtain a moment of the area under the curve through equation 2 to obtain the stability of MIT and Windstar TLP [11].

$$m_n = \frac{1}{3}\ x\ \Delta\omega\ x\ \Sigma n \qquad (2)$$

where =

m_n = Area under the response spectrum curve (n order moment)

$\Delta\omega$ = Frequency interval (rad/s)

Σn = The cumulative result of the n table row sum (m^2/(rad/s) or $degrees^2$/(rad/s) depending on the direction of movement of the floating structure)

Table 4. MIT TLP and Windstar TLP Specifications [2,3]

MIT TLP (1 column TLP)		**Windstar TLP (4 column TLP)**	
Platform diameter	18 m	Center column diameter	6 m
Draft	47,89 m	Corner column diameter	4,8 m x 4,8 m
Number of pontoons	4	Distance of center column andcorner column	20 m
Pontoon diameter	27 m	Moulded depth	42,8 m
Average mooring system tension per line	3.931 kN	Draft	21,5 m
Concrete mass	8.216.000 kg	Air gap	21,3 m
Concrete height	12,6 m	Platform mass	1770 t
Total displacement	12.187.000 kg	Platform mass vertical centre (measure from keel)	9,85 m
Number of mooring lines	8	Upper pontoon dimensions	4,8 m x 3,5 m
Line diameter	0,127 m	Lower pontoon dimensions	4,8 m x 5 m
Steel wall thickness	0,015 m	Pretension	1950 t
Center of Gravity	22,79 m	Total displacement	4275 t
Center of Buoyancy	23,95 m	Tendon diameter	239 mm
The distance of the tendon attachment point from the centralaxis of the TLP	27 m	The distance of the tendon attachment point from the centralaxis of the TLP	39 m

Meanwhile, the equation to obtain structural stability is based on the equation for the significant wave amplitude in equation 3 [12]. The value of m_0 in the equation will be replaced by m_0 in the calculation of the response spectrum so the equation produces structural stability in the direction of pitch movement.

$$Significant\ Wave\ Amplitude = 2\sqrt{m_0} \quad (3)$$

Besides RAO, Joint North Sea Wave Atmosphere Program (JONSWAP) wave spectrum was also used for the calculation of the response spectrum. The JONSWAP wave spectrum was chosen because it is suitable to be applied to closed waters such as Indonesian waters which consist of various islands. The equation for the JONSWAP spectrum model can be seen as follows [13].

$$S(\omega) = \bar{\beta} g^2 \omega^{-5} \exp\left(-1{,}25 \left[\frac{\omega}{\omega_o}\right]^{-4}\right) x\ \gamma^{\left[\exp\left(-\frac{(\omega-\omega_o)^2}{2\sigma^2\omega_o^2}\right)\right]} \quad (4)$$

where =

g = Peakedness parameter

$\bar{\beta}$ = Phillips constant modification

σ = Spectrum width parameters

= 0,07, if $\omega \leq \omega_o$

= 0,09, if $\omega \geq \omega_o$

ω_o = 0,161g/Hs

Hs	= Significant wave height
Ts	= Significant wave period

For peakedness parameters, can be obtained through the equation below.

$$\gamma = 5 \qquad \text{if } T_s/\sqrt{H_s} \leq 3,6 \tag{5}$$

$$\gamma = \exp(5,75 - 1,15\frac{T_s}{\sqrt{H_s}}) \qquad \text{if } T_s/\sqrt{H_s} > 3,6 \tag{6}$$

As for the modification of the Phillips constant in the application in the North Sea, it can be obtained through the following equation below or can use the value of 0.0081 if the modification number of the Phillips constant is not known.

$$\beta = 5,058\,(\frac{H_s}{(T_s)^2})\,(1 - 0,287\ln\gamma) \tag{7}$$

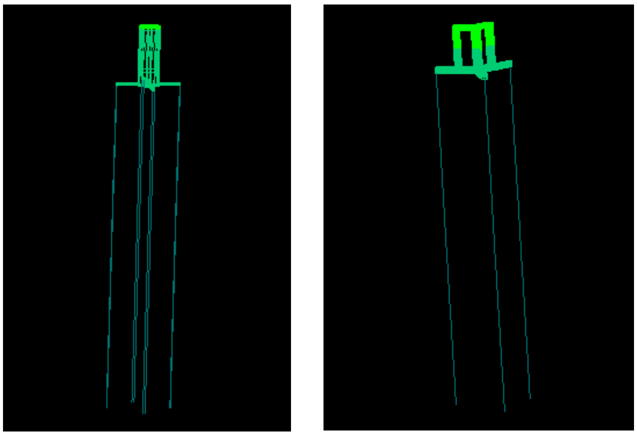
After obtaining the stability of the structure, the stability criteria can be determined. The stability criteria for supporting structures for offshore wind turbines are as follows.

- Operating ≤ 0,7°
- Survival ≤ 2,0°
- Stand By ≤ 6,0°
- Damaged ≤ 18,0°

In operating criteria, offshore wind turbines can still operate normally. Survival criteria are a condition of stability one level above operating where the wind turbine can still work. The stand-by criterion is a condition where the wind turbine is stopped operating. Then, the damaged criteria are conditions that can cause damage to the structure of the offshore wind turbine [3].

3 Results and discussion

The MIT and Windstar TLP modeling was carried out using Moses based on the available specification data. The calculation assumption used is the radius of gyration because there is no such data for input for Windstar TLP modeling. The calculation of the radius of gyration for Windstar TLP is based on the calculation of the Efunda reference. The results of the radius of gyration obtained are the radius of gyration on the x-axis of 9,037 m, the radius of gyration on the y-axis of 11,423 m, and the radius of gyration on the y-axis of 7,031 m. The model of MIT and Windstar TLP structure from Moses can be seen in figure 3. Besides that, Moses also calculated MIT and Windstar RAO data that will be used for calculating the response spectrum. RAO data for pitch movement can be seen in column 4 of table 7 and 10.



(a) (b)

Fig 3. (a) MIT TLP (1 column); (b) Windstar TLP (4 columns)

3.1. Model verification

In modeling verification, the center of buoyancy of Windstar TLP data sourced from calculation assumptions is used. The assumption of calculating the center of buoyancy is used based on the Bockute reference with the result that the center of buoyancy is 7,55 m [3].

In table 5, the results show that the modeling in Moses is quite to the previous research's MIT and Windstar TLP specifications with a modeling difference that is quite close to 1,98% where 1,98% is a reference to the difference in the verification of floating structure modeling so that the MIT and Windstar modeling can proceed to the next analysis.

In table 5, it is known that the difference in the verification results for MIT and Windstar TLP is greater than the reference difference of 1.98%. This is probably due to the limitations of input data and differences in the use of software between the one used for this study (Moses) and that used in the previous MIT TLP and Windstar TLP study where the MIT TLP research used WAMIT software and the Windstar TLP research used Sesam software, causing differences in model verification results. In addition, the verification result of Windstar TLP modeling is greater than that of MIT TLP. This happens because of the limited modeling data available for Windstar TLP, so it uses modeling input data based on the assumptions of theoretical calculations. The radius of gyration which is used as input for modeling in Moses is obtained based on the calculation of the theory of Efunda. In addition, the center of buoyancy of Windstar TLP reference uses calculation assumptions based on the Bockute reference theory. Therefore, because some data are not available in the Windstar TLP reference which must use theoretical calculation assumptions to replace it, the author considers that the result of the Windstar TLP verification difference is larger than the MIT TLP is still reasonable.

Table 5. MIT and Windstar TLP Modeling Verification

	MIT TLP		Difference
	Moses	**Reference**	
Displacement	12449109,072 kg	12187000 kg	2,15 %
Center of Buoyancy	23,44	23,95	2,12 %
	Windstar TLP		
Displacement	4470169,215 kg	4275000 kg	4,565 %
Center of Buoyancy	6,44 m	7,55 m	14,7 %

3.2. Calculation of the MIT TLP and windstar TLP response spectrum

The calculation of the response spectrum is carried out between RAO in the direction of pitch movement and the JONSWAP wave spectrum as shown in table 7. Table 7 shows the calculation of the response spectrum for the 100-years environmental condition forces in the direction of 0 degrees where that environmental force is the largest environmental force among other environmental forces. The difference in environmental forces for the response spectrum can be found in JONSWAP wave spectrum which uses the height and period of wave depending on the environmental conditions. In addition, the calculation of the response spectrum for other environmental force conditions has the same calculation process as in table 7. After getting Σ0 through the calculation table of the response spectrum for all environmental force conditions, calculations are carried out to obtain the stability of MIT and Windstar TLP in the direction of pitch movement. The results of the MIT and Windstar TLP stability based on the structural stability equation are as follows.

Table 6. MIT TLP and Windstar TLP Pitch Movement Stability

	MIT TLP	**Windstar TLP**
10-years environmental forces in the direction of 0 degrees	0,383°	0,081°
10-years environmental forces in the direction of 45 degrees	0,283°	0,066°
100-years environmental forces in the direction of 0 degrees	0,501°	0,116°
100-years environmental forces in the direction of 45 degrees	0,436°	0,094°

3.3. Stability criteria of MIT TLP and windstar TLP as support structures for offshore wind turbines

From the determination of the stability criteria in table 8, the results show that all the stability of the direction of pitch movement for MIT TLP and Windstar TLP in 4 different environmental conditions have the same stability criteria, namely operating. So, it can be interpreted that offshore wind turbines can operate normally with MIT TLP and Windstar TLP as supporting structures in the Makassar Strait waters.

Tabel 8. Offshore Wind Turbine Stability Criteria for MIT TLP and Windstar TLP Based on Rick Mercier's Stability Criteria

	MIT TLP	Rick Mercier's Stability	WindstarTLP	Rick Mercier's Stability
10-years environmental force in the direction of 0 degrees	0,383°	≤ 0,7° (*operating*)	0,081°	≤ 0,7° (*operating*)
10-years environmental force in the direction of 45 degrees	0,283°	≤ 0,7° (*operating*)	0,066°	≤ 0,7° (*operating*)
100-years environmental forcein the direction of 0 degrees	0,501°	≤ 0,7° (*operating*)	0,116°	≤ 0,7° (*operating*)
100-years environmental forcein the direction of 45 degrees	0,436°	≤ 0,7° (*operating*)	0,094°	≤ 0,7° (*operating*)

3.4. Comparative analysis of the stability of MIT TLP and windstar TLP

Stability at 100 years of environmental force in the direction of 0 degrees will be used as a reference for comparison because it is the greatest stability in MIT TLP and Windstar TLP of all environmental forces. In addition, the stability comparison shows that the Windstar TLP (0,116°) has better stability than the MIT TLP stability (0,501°). With the results of the stability comparison, the column configuration of the Windstar TLP will be reused for the analysis of the comparison of TLP stability between 1 and 2 tendons. From this comparison, the difference in response spectrum is the cause of the difference in stability between the MIT and Windstar TLP. The results of the MIT and Windstar TLP response spectrum have been graphed and can be seen in Figure 4 with a blue curve for MIT TLP and an orange curve for Windstar TLP. The two curves show the results of the response spectrum at each frequency. Figure 4 shows that the MIT TLP response spectrum dominates the Windstar TLP response spectrum along with a frequency of 0,45 – 1,6 rad/s with a maximum response spectrum of 0,12 ($°^2$/(rad/s)). By dominating the response spectrum, the result of Σ0 which is the basis for calculating the moment area under the spectrum curve and stability for MIT TLP is greater than Σ0 Windstar TLP where Σ0 MIT TLP is 3,765 while Σ0 Windstar TLP is 0,201 as can be seen in table 7.

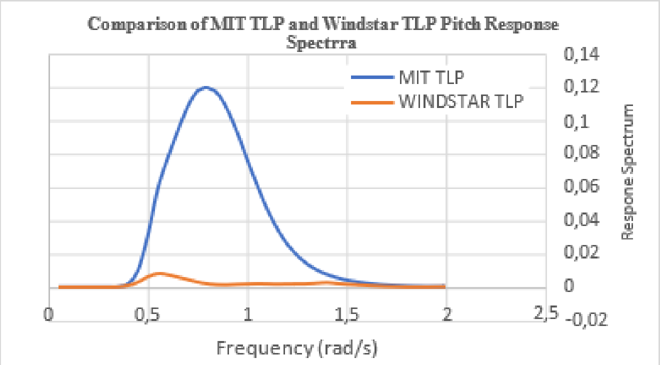


Fig. 4. Comparison of MIT TLP and Windstar TLP Pitch Response Spectrum

Table 7. Calculation of Response Spectrum of MIT and Windstar TLP for 100-year environmental force inthe direction of 0 degrees

1	2	3	4		5		6		7	
ω (rad/s)	Spektra	SM	RAO		RAO^2		Sr		Sr*SM	
			MIT	Windstar	MIT	Windstar	MIT	Windstar	MIT	Windstar
0,05	0	1	0,049	0,024	0,002401	0,000576	0	0	0	0
0,1	0	4	0,027	0,016	0,000729	0,000256	0	0	0	0
0,15	9,23611E-79	2	0,019	0,013	0,000361	0,000169	3,33E-82	1,5609E-82	6,6685E-82	3,1218E-82
0,2	2,66833E-23	4	0,014	0,012	0,000196	0,000144	5,23E-27	3,84239E-27	2,092E-26	1,53696E-26
0,25	1,85441E-08	2	0,009	0,01	0,000081	0,0001	1,5E-12	1,85441E-12	3,0041E-12	3,70882E-12
0,3	0,002385168	4	0,008	0,013	0,000064	0,000169	1,53E-07	4,03093E-07	6,106E-07	1,61237E-06
0,35	0,252774286	2	0,016	0,017	0,000256	0,000289	6,47E-05	7,30518E-05	0,00012942	0,000146104
0,4	1,813277374	4	0,03	0,021	0,0009	0,000441	0,001632	0,000799655	0,0065278	0,003198621
0,45	4,210616419	2	0,048	0,025	0,002304	0,000625	0,009701	0,002631635	0,01940252	0,005263271
0,5	6,494096939	4	0,069	0,03	0,004761	0,0009	0,030918	0,005844687	0,12367358	0,023378749
0,55	6,70555234	2	0,094	0,034	0,008836	0,001156	0,05925	0,007751619	0,11850052	0,015503237
0,6	5,131079801	4	0,123	0,037	0,015129	0,001369	0,077628	0,007024448	0,31051243	0,028097793
0,65	3,953965142	2	0,154	0,038	0,023716	0,001444	0,093772	0,005709526	0,18754447	0,011419051
0,7	3,108676465	4	0,187	0,037	0,034969	0,001369	0,108707	0,004255778	0,43482923	0,017023112
0,75	2,423038306	2	0,221	0,034	0,048841	0,001156	0,118344	0,002801032	0,23668723	0,005602065
0,8	1,879674958	4	0,253	0,031	0,064009	0,000961	0,120316	0,001806368	0,48126446	0,007225471
0,85	1,459734922	2	0,283	0,03	0,080089	0,0009	0,116909	0,001313761	0,23381742	0,002627523
0,9	1,138723549	4	0,307	0,033	0,094249	0,001089	0,107324	0,00124007	0,42929422	0,00496028
0,95	0,893973653	2	0,323	0,041	0,104329	0,001681	0,093267	0,00150277	0,18653475	0,003005539
1	0,706971478	4	0,33	0,049	0,1089	0,002401	0,076989	0,001697439	0,30795678	0,006789754
1,05	0,563403447	2	0,331	0,057	0,109561	0,003249	0,061727	0,001830498	0,12345409	0,003660996
1,1	0,452485421	4	0,323	0,062	0,104329	0,003844	0,047207	0,001739354	0,18882941	0,006957416
1,15	0,366184569	2	0,311	0,067	0,096721	0,004489	0,035418	0,001643803	0,07083548	0,003287605

1,2	0,298538554	4	0,296	0,075	0,087616	0,005625	0,026157	0,001679279	0,10462702	0,006717117
1,25	0,245117465	2	0,28	0,085	0,0784	0,007225	0,019217	0,001770974	0,03843442	0,003541947
1,3	0,202617874	4	0,263	0,095	0,069169	0,009025	0,014015	0,001828626	0,0560595	0,007314505
1,35	0,168563436	2	0,246	0,113	0,060516	0,012769	0,010201	0,002152387	0,02040157	0,004304773
1,4	0,141086357	4	0,231	0,133	0,053361	0,017689	0,007529	0,002495677	0,03011404	0,009982706
1,45	0,118768457	2	0,216	0,13	0,046656	0,0169	0,005541	0,002007187	0,01108252	0,004014374
1,5	0,100525531	4	0,202	0,127	0,040804	0,016129	0,004102	0,001621376	0,01640738	0,006485505
1,55	0,085522954	2	0,19	0,122	0,0361	0,014884	0,003087	0,001272924	0,00617476	0,002545847
1,6	0,07311382	4	0,175	0,113	0,030625	0,012769	0,002239	0,00093359	0,00895644	0,003734361
1,65	0,062793352	2	0,159	0,098	0,025281	0,009604	0,001587	0,000603067	0,00317496	0,001206135
1,7	0,054165098	4	0,142	0,083	0,020164	0,006889	0,001092	0,000373143	0,00436874	0,001492573
1,75	0,046915715	2	0,124	0,067	0,015376	0,004489	0,000721	0,000210605	0,00144275	0,000421209
1,8	0,040796039	4	0,107	0,051	0,011449	0,002601	0,000467	0,00010611	0,0018683	0,000424442
1,85	0,035606772	2	0,091	0,039	0,008281	0,001521	0,000295	5,41579E-05	0,00058972	0,000108316
1,9	0,031187604	4	0,081	0,042	0,006561	0,001764	0,000205	5,50149E-05	0,00081849	0,00022006
1,95	0,027408893	2	0,083	0,063	0,006889	0,003969	0,000189	0,000108786	0,00037764	0,000217572
2	0,024165247	1	0,102	0,095	0,010404	0,009025	0,000251	0,000218091	0,00025142	0,000218091
								Σ0	**3,76494406**	**0,201097733**

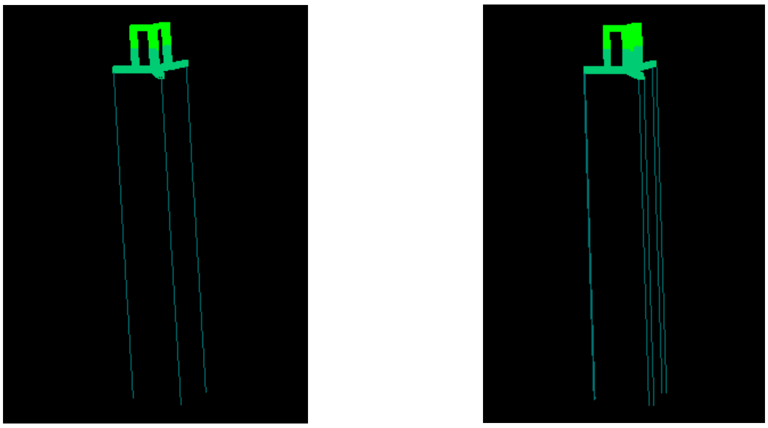
Besides that, the area of the base structure can also affect the stability results. According to Xunta de Galicia, when the base area of the structure gets bigger, the structure becomes more stable [3]. Table 9 shows that the base area of the Windstar TLP (546,674 m2) is larger than the MIT TLP (392,709 m2). The two results of the base area of the structure have a difference of 32,78%. The results of the comparison of the basic area of the structure are appropriate with the Xunta de Galicia reference which states that the wider the base of the structure, the more stable the structure.

Table 9. Base Area of MIT TLP and Windstar TLP Structure

	Base Area Structure (m^2)
MIT TLP	392,709
Windstar TLP	546,674

3.5. Windstar TLP 1 and 2 tendons modeling

This time, the Windstar TLP was modeled with 1 and 2 tendons. Windstar TLP modeling with 1 tendon has been carried out at the beginning of chapter 3 which can be seen in Figure 7(a). In addition, Windstar TLP modeling with 2 tendons at each end of the lower pontoon can be seenin Figure 7 (b). In addition, Windstar TLP with 2 tendons RAO data is also obtained from Moses who performs the calculation of RAO.



(a) (b)

Fig. 5. (a) Windstar TLP Model with 1 Tendon at Each End of the Lower Pontoon; (b) Windstar TLP Model with 2 Tendons at Each End of the Lower Pontoon

Table 10. Calculation of Response Spectrum of Windstar TLP 1 and 2 Tendons for 100-year environmental force in the direction of 0 degrees

1	2	3	4	5	6	7
ω (rad/s)	**Spektra**	**SM**	**RAO**	**RAO^2**	**Sr**	**Sr*SM**
0,05	0	1	0,02	0,0004	0	0
0,1	0	4	0,013	0,000169	0	0
0,15	9,24E-79	2	0,01	0,0001	9,236E-83	1,85E-82
0,2	2,67E-23	4	0,009	0,000081	2,161E-27	8,65E-27
0,25	1,85E-08	2	0,007	0,000049	9,087E-13	1,82E-12
0,3	0,002385	4	0,009	0,000081	1,932E-07	7,73E-07
0,35	0,252774	2	0,01	0,0001	2,528E-05	5,06E-05
0,4	1,813277	4	0,012	0,000144	0,0002611	0,001044
0,45	4,210616	2	0,014	0,000196	0,0008253	0,001651
0,5	6,494097	4	0,016	0,000256	0,0016625	0,00665
0,55	6,705552	2	0,018	0,000324	0,0021726	0,004345
0,6	5,13108	4	0,019	0,000361	0,0018523	0,007409
0,65	3,953965	2	0,019	0,000361	0,0014274	0,002855
0,7	3,108676	4	0,019	0,000361	0,0011222	0,004489
0,75	2,423038	2	0,017	0,000289	0,0007003	0,001401
0,8	1,879675	4	0,015	0,000225	0,0004229	0,001692
0,85	1,459735	2	0,014	0,000196	0,0002861	0,000572
0,9	1,138724	4	0,015	0,000225	0,0002562	0,001025
0,95	0,893974	2	0,018	0,000324	0,0002896	0,000579
1	0,706971	4	0,022	0,000484	0,0003422	0,001369
1,05	0,563403	2	0,025	0,000625	0,0003521	0,000704
1,1	0,452485	4	0,027	0,000729	0,0003299	0,001319
1,15	0,366185	2	0,029	0,000841	0,000308	0,000616
1,2	0,298539	4	0,032	0,001024	0,0003057	0,001223
1,25	0,245117	2	0,035	0,001225	0,0003003	0,000601
1,3	0,202618	4	0,04	0,0016	0,0003242	0,001297
1,35	0,168563	2	0,046	0,002116	0,0003567	0,000713
1,4	0,141086	4	0,053	0,002809	0,0003963	0,001585
1,45	0,118768	2	0,05	0,0025	0,0002969	0,000594

1,5	0,100526	4	0,048	0,002304	0,0002316	0,000926
1,55	0,085523	2	0,045	0,002025	0,0001732	0,000346
1,6	0,073114	4	0,041	0,001681	0,0001229	0,000492
1,65	0,062793	2	0,034	0,001156	7,259E-05	0,000145
1,7	0,054165	4	0,028	0,000784	4,247E-05	0,00017
1,75	0,046916	2	0,022	0,000484	2,271E-05	4,54E-05
1,8	0,040796	4	0,016	0,000256	1,044E-05	4,18E-05
1,85	0,035607	2	0,012	0,000144	5,127E-06	1,03E-05
1,9	0,031188	4	0,012	0,000144	4,491E-06	1,8E-05
1,95	0,027409	2	0,017	0,000289	7,921E-06	1,58E-05
2	0,024165	1	0,025	0,000625	1,51E-05	1,51E-05
					Σ0	**0,04601**

3.6. Calculation of windstar TLP 1 and 2 tendons response spectrum

Table 10 shows the calculation of the response spectrum of Windstar TLP 1 and 2 tendons at the 100-years environmental condition forces in the direction of 0 degrees where that environmental force is the largest environmental force from other environmental forces. In addition, the calculation of the response spectrum for other environmental force conditions has the same calculation process as in table 10.

After getting Σ0 through the response spectrum calculation table, calculations are carried out to obtain the stability of Windstar TLP 1 and 2 tendons in the direction of pitch movement. The results of TLP stability based on the structural stability equation are as follows.

Table 11. Windstar TLP 1 and 2 Tendons Pitch Movement Stability

	1 tendon	**2 tendons**
10-years environmental forces in the direction of 0 degrees	0,081°	0,036°
10-years environmental forces in the direction of 45 degrees	0,066°	0,027°
100-years environmental forces in the direction of 0 degrees	0,116°	0,055°
100-years environmental forces in the direction of 45 degrees	0,094°	0,043°

3.7. Stability criteria of windstar TLP 1 and 2 tendons as supporting structures for offshore wind turbines

Table 12 shows that all Windstar TLP stability results with 1 and 2 tendons under different environmental conditions have operating stability criteria. Therefore, it can be interpreted that offshore wind turbines can work normally with a supporting structure in the form of Windstar TLP with 1 tendon or 2 tendons at each end of the lower pontoon.

Table 12. Offshore Wind Turbine Stability Criteria for Windstar TLP with 1 Tendon and 2 Tendons Based on Rick Mercier Stability Criteria

	Windstar TLP with 1 tendon	**Rick Mercier's Stability**	**Windstar TLP with 2 tendons**	**Rick Mercier's Stability**
10-years environmental force in the direction of 0 degrees	0,081°	≤ 0,7° (*operating*)	0,036°	≤ 0,7° (*operating*)
10-years environmental force in the direction of 45 degrees	0,066°	≤ 0,7° (*operating*)	0,027°	≤ 0,7° (*operating*)
100-years environmental force in the direction of 0 degrees	0,116°	≤ 0,7° (*operating*)	0,055°	≤ 0,7° (*operating*)
100-years environmental force in the direction of 45 degrees	0,094°	≤ 0,7° (*operating*)	0,043°	≤ 0,7° (*operating*)

3.8. Comparative analysis of stability between windstar TLP 1 and 2 tendons

Stability at 100 years of environmental force in the direction of 0 degrees will be used as a reference for comparison because it is the greatest stability in Windstar TLP 1 and 2 tendons of all environmental forces. In addition, the stability comparison shows that the stability of Windstar TLP with 1 tendon (0,116°) is greater than Windstar TLP with 2 tendons (0,055°) at each end of the lower pontoon. With these results and combined with the results of comparisons between TLP columns, the most stable TLP configuration as a support structure for offshore wind turbines is TLP with a 4 columns configuration (Windstar TLP) with 2 tendons at each end of the lower pontoon. In the stability comparison that has been carried out, the difference in response spectrum is the cause of the difference in stability between the Windstar TLP 1 and 2 tendons. The results of the response spectrum of Windstar TLP 1 and 2 tendons have been graphed and can be seen in Figure 6 with a blue curve for the Windstar TLP 1 tendon and an orange curve for the Windstar TLP 2 tendons. The two curves show the results of the response spectrum at each frequency. Figure 6 shows that the response spectrum of the Windstar TLP 1 tendon dominates the response spectrum of the Windstar TLP 2 tendons along with a frequency of 0,4 – 1,8 rad/s with a maximum response spectrum of 0,0077 ($°^2$/(rad/s)). By dominating the response spectrum, the result of Σ0 which is the basis for calculating the moment area under the spectrum curve and stability for Windstar TLP 1 tendon is greater than Σ0 Windstar TLP 2 tendons where Σ0 Windstar TLP 1 tendon is 0,201 while Σ0 Windstar TLP 2 tendons is 0,046.

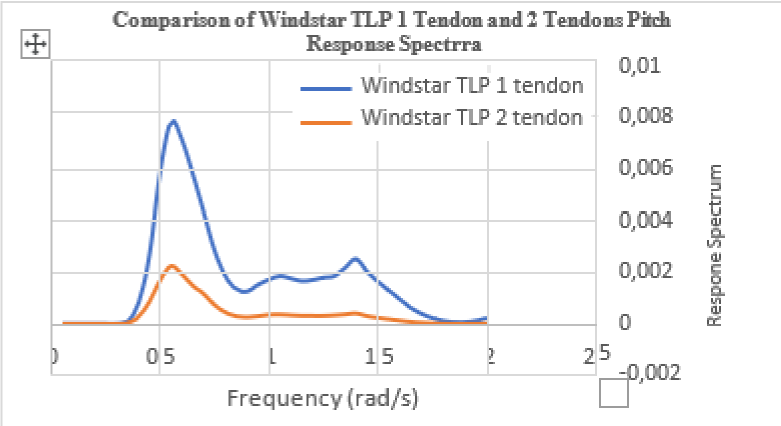


Fig. 6. Comparison of Windstar TLP 1 Tendon and 2 Tendons Pitch Response Spectrum

4 Conclusion

Based on the research that has been done, MIT TLP and Windstar TLP can be used as supporting structures for offshore wind turbines in the Makassar Strait based on the Rick Mercier stability criteria because they have operating stability criteria as shown in tables 8 and 12. In addition, by combining the results of the comparison between columns and tendons that have been carried out, the most stable TLP configuration as a supporting structure for offshore wind turbines in the Makassar Strait is TLP with 4 columns configuration (Windstar TLP) and 2 tendons at each end of the lower pontoon.

References

[1] Bachynski EE, Moan T. Design Considerations for tension leg platform wind turbines. Marine Structures. 2012;29(1):89-114. p. 90. Doi: https://doi.org/10.1016/j.marstruc.2012.09.001.

[2] Matha D. Model development and loads analysis of an offshore wind turbine on a tension leg platform, with a comparison to other floating turbine concepts. Colorado: National Renewable Energy Laboratory;2009.

[3] Zhao Y, Yang J, He Y. Preliminary design of a multi-column TLP foundation for a 5-MW offshore wind turbine. Energies. 2012;5(12):3875-3891. Doi: :10.3390/en5103874

[4] Tabeshpour MR, Ahmadi A, Malayjerdi I. Investigation of TLP behavior under tendon damage. Ocean Engineering. 2018;156:580-595.

[5] Chatterjee PC. Computer-aided reliability-based hydro-structural response analysis of tension leg platforms [PhD Thesis]. Glasgow, Scotland: University of Glasglow; 1995.

[6] Jonkman JM. Dynamics modeling and loads analysis of an offshore floating wind turbine [Internet]. National Renewable Energy Laboratory, A national laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy; 2007 November. Available from: https://www.nrel.gov/docs/fy08osti/41958.pdf

[7] Hendi IR. Analisa stabilitas turbin angin terapung lepas pantai tipe sistem tension leg platform: Stability analysis of floating offshore wind turbine tension led platform system type [Thesis]. Depok: Universitas Indonesia; 2011.

[8] Klara S, Had AL, Baharuddin, Pawara MU. Kajian potensi energi dan angin di Perairan Barat dan Selatan Pulau Sulawesi [Internet]. Prosiding 2013, Hasil Penelitian Fakultas Teknik Universitas Hasanuddin; 2013. Available from: https://nanopdf.com/download/kajian-potensi-energi-angin-di-perairan-barat-dan_pdf.

[9] Cendrawani C, Djatmiko EB, Sutomo J. Studi komparasi perilaku dinamis tension leg platform kolom tunggal bertelapak kaki bintang tiga dan bintang empat dengan pendekatan pembebanan berdasar teori morison dan difraksi. Jurnal Teknik ITS. 2012;1:155-160. Vol. 1. Pp. 155-160. DOI: 10.12962/j23373539.v1i1.1796

[10] Chakrabarti SK. Hydrodynamics of offshore structures. New York. Springer;1987.

[11] Djatmiko EB. Perilaku dan operabilitas bangunan laut di atas gelombang acak. Surabaya: ITS Press; 2012.

[12] Dinaryo M. Studi operabilitas spar platform tipe truss di selat makassar dengan sistem tambat taut [Final Project]. Surabaya: Institut Teknologi Sepuluh November; 2016.

[13] Chakrabarti SK. Handbook of offshore engineering. Oxford: Elsevier; (2005).

[14] Efunda. efunda.com/home.cfm. [Online]. Efunda; 2022. Available from: https://www.efunda.com/home.cfm.

[15] Bockute I. Buoyancy and stability analysis of floating offshore wind turbines dundee [Honours Project Thesis]. Dundee: University of Dundee; 2019.

[16] Xunta de Galicia. Structural analysis and conditions [Internet]. Xunta de Galicia; 2022. Available from: https://www.edu.xunta.gal/centros/cafi/aulavirtual/pluginfile.php/40113/mod_imscp/content/1/a_stable_resistant_and_rigid_structure.html.