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Investigation of Available Configurations for Flexible Risers in Shallow Water

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ABSTRACT

Flexible risers have been used widely in recent years for floating structure in shallow and deep water. Flexible risers have various configurations and each configuration has its specific charectresitics that helps the riser to solve the problems that exist in shallow and deep water. Selecting and designing the best configuration for flexible risers in shallow water, like deep water, present many challenges, some of these challenges can be addressed: high vessel displacement compared to the water depth, minimum riser clearance with the seabed or sea surface or the vessel keel, bending radius limitation and etc. The aim of this paper is to investigate the traditional configurations like lazy wave and pliant wave and to compare them with a new configuration like weight added wave for the riser with 15 inches internal diameter in 45m water depth connected to a turret moored floating storage unit. It is concluded that the traditional configuration can not solve the sea surface clearance problem when the riser is empty condition, in this condition the weight of riser is decreased and the buoyancy force is become higher than riser weight and lift the riser up and the riser become flooded on the sea surface. To preventing the riser from flooding on the sea surface it's needed to use configuration with added mass. Also concluded that using added mass in touch down zone (TDZ) reduces the tension in PLEM connection point about 89% . Also concluded that the minimum bending radius for weight added wave configuration is increased about 29% in compared with traditional configurations.

1. Introduction

Flexible risers are a proven technology for the production of oil and gas and are used widely in the offshore industry since 1970 [1]. Flexible risers are one of the most important structures that are used widely for transportation of hydrocarbons and because of their high axial stiffness and low bending stiffness compared to steel risers are used mostly in shallow water, these properties cause the riser to accommodate a large deformation generated by floating structure motions and ocean waves and currents [2], [3].

Flexible risers have different configurations and these configurations have different characteristics and these characteristics influence the riser ability to solve the challenges in shallow water. One of the most important things in the designing configuration is that the riser should not experience excessive curvature and this maximum allowable curvature is determined by riser manufacture [3].

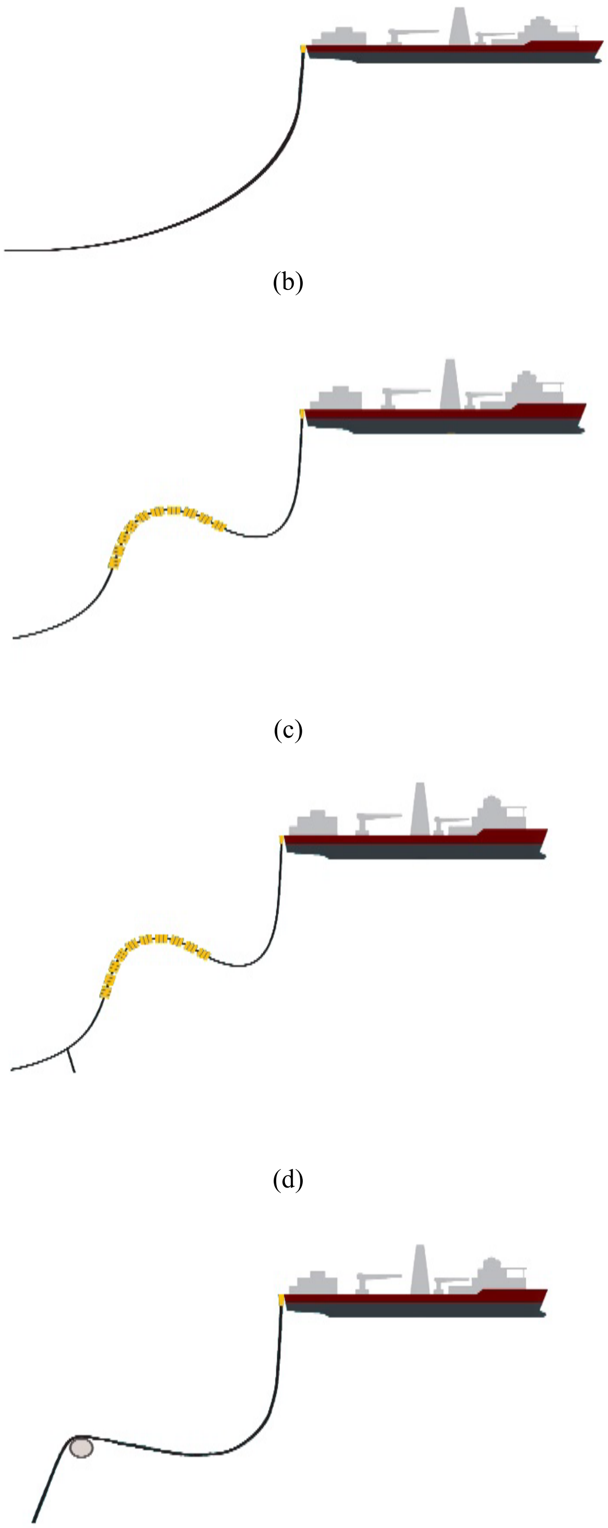
Floating structure motions due to wave load create a tensile and bending moment in the riser, the configuration should be designed to minimize this forces in riser and also the configuration should be chosen that the effect of floating motions in touch down point (TDP) is minimized [2], [4].

Challenges in the design of flexible riser's configuration in shallow water are [4], [5], and [6]:

- High vessel displacement compared to the water depth
- Wave and current loads effect on the riser
- Short distance between vessel and seabed
- Risers clearance between sea bed or sea surface
- Riser weight changes and marine growth weight affects the static position of the riser

Traditional configurations for flexible riser in shallow water are: catenary, lazy wave, pliant wave, and S and they are shown in figure 1- a-d respectively [3], [7].

(a)


(b)

(c)

(d)

(e)

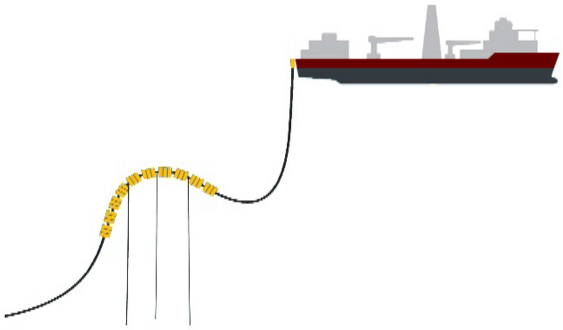


Figure 1. Flexible riser configurations for shallow water; a) catenary configuration, b) Lazy wave configuration, c) Pliant wave configuration, d) Steep S configuration, e) Weight added wave (WAW) configuration

As shown in figure above, the catenary configuration is the simplest configuration and because of high lateral displacement and its inability to accommodate deformations due to vessel motions and wave load not suitable for shallow water. Also the S configuration needs a mid-water arc and constructing this arc is difficult and very expensive than other configuration so this configuration is not much of a use in shallow water. Lazy wave and pliant wave configuration have a buoyancy zone that helps the configuration to accommodate the deflection and prevents it from making high stress in the touch down zone (TDZ) and PLEM connection point. The difference between lazy wave and pliant wave configurations is that the pliant wave configuration has a tether that helps this configuration to limit the transverse displacement and reduces the risk of clash between the riser and other facilities that are located underwater.

One of the most important problems arising when using traditional configuration in shallow water is the riser clearance with the seabed or sea surface. When the riser content is light or riser in empty condition the clearance between riser and sea surface become a big problem. Also when the riser content is heavy oil the clearance between the riser and seabed make a big challenge [8].

The weight added wave (WAW) configuration has been made up from adding drag chains to some of the buoyancy modules of lazy wave configuration. It is common to use three drag chains to make WAW configuration, the end of these chains is laid on the seabed and makes equilibrium between riser weight and buoyancy force. When risers are in operating condition and riser weight increases the chains laid on the seabed and helps to make equilibrium and when the riser is in empty condition the chains are lifted from seabed and help riser to prevent them from floating on sea surface. The WAW configuration is shown in figure 1-e [1], [8].

Some studies have been already conducted on flexible riser configuration in shallow water such as:

Hanonge et al. [9] investigated the existing problems and challenges in designing flexible riser configuration in shallow water and gave a solution for each problem, and also investigated the S and pliant wave configuration for 4 inches and 10 inches risers in shallow water and concluded that the S configuration has more challenges than pliant wave configuration. Li et al. [10]investigated the lazy wave configuration for 8 inches riser connected to a turret moored FPSO and concluded that the lazy wave configuration shows the good response for riser in severe condition in 300m water depth. Tan et al. [1] introduced the weight added wave (WAW) configuration to the offshore industry for the shallow water, this configuration made up as chains connected to the buoyancy modules of lazy wave configuration and this chains help the riser to balance the weight force and also investigate this configuration for the 8 inches riser connected to the turret moored FPSO and compared this configuration with lazy wave configuration and concluded that the weight added wave configuration has fewer challenges and risk than lazy wave configuration. Gurung et al. [11]provide an optimization method for lazy wave configuration by attaching the weight chains to lazy wave buoyancy module and investigate the influence of chains weight and length and their location along the riser on its behavior to solve the challenges facing in shallow water, compared the optimized configuration with pliant and lazy wave configuration for 10 inches riser and concluded that the optimized configuration has less lateral displacement and more seabed and sea surface clearance than lazy wave and pliant wave configuration. Karegar [3] Investigated the lazy wave and pliant wave configurations for flexible riser in shallow water for internal turret FPSO and also proposed the touch down chain configuration and concluded that the double wave configuration is not a suitable choice for shallow water condition with harsh environmental and also the riser size should be small as possible and recommended that the 10inches riser is suitable for shallow water , and also concluded that the pliant wave configuration has the best performance in shallow water in compared with lazy wave configuration. Hou et al. [10] investigated the design challenges encountered in a flexible riser application with an external turret moored FSO in shallow water and introduced a soloution for these challenges by an improved lazy wave configuration. One of the most important desing challenges of flexible riser configuration is riser bending radius and also riser interfrences with the seabed, in this paper an improved lazy wave configuration was introduced, for this improved configuration the ballast modules were used innovatively to maintain the configuration in suspension by automatically compensating the riser weight variation during entire service period and concluded that the improved configuration has more clearance with seabed and sea surface than lazy wave configuration but the riser radius for this configuration is less than lazy wave configuration.

This paper deals with the static and dynamic analysis of lazy wave and pliant wave configuration and compares them with WAW configuration for 15 inches flexible riser connected to a turret moored FSU in shallow water (50m water depth). The static and dynamic analysis is done by Orcaflex software.

2. Methodology

For typical flexible riser configuration such as lazy wave, a global analysis should perform to identify the maximum response of the riser system under extreme functional, accidental and environmental load. For this procedure, the data of extreme environmental, functional and accidental loads should be collected. The global analysis is divided into two parts [12]:

- Static analysis
- Dynamic analysis

2.1. Design Criteria

Design of flexible riser configuration has certain criteria and they are [12], [13]:

- Riser can accommodate vessel displacement due to wave and current
- Riser behavior near connections to the turret and PLEM
- Minimum bending radius
- Seabed and sea surface clearance
- Prevent from the clash with other risers and facilities located underwater

2.2. Global model of flexible riser

For line modeling, the Orcaflex using spring dampers that model the structural properties of the line shown in figure 2. As shown in figure 2 the model consists of several segments and nodes. A line divided into several segments which are then modeled by massless segment and node at end of each segment. The model segment only models the torsional and axial properties of the riser, other loads such as weight, buoyancy and etc. are lumped at each node. Each segment divided into two halves, and the segment halves properties that are lumped and assigned to the node at the end of the segment [14].

The bending properties of the line are defined by a spring-damper model at each end of the segment, between the segment and the node [14].

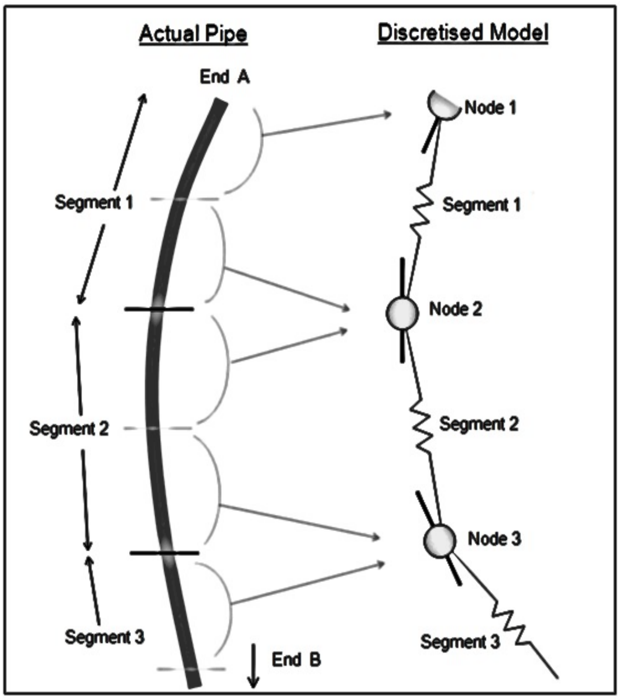


Figure 2. Line modeling in orcaflex software for riser and mooring lines [14]

Riser and FPSO modeling in orcafelx software is shown in figure 3.

Figure 3. Lazy wave configuration modeling in orcaflex software in the loaded condition

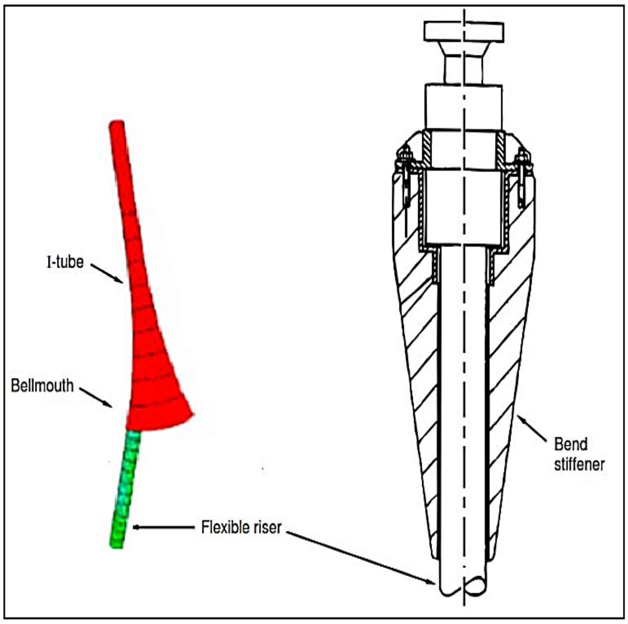
As shown in figure above at the hang-off point, the point that riser connects to the vessel, the bend stiffener and riser are modeled as being vertically fixed to the bottom of the turret.

The bottom part of the riser lies on the seabed and is connected to a PLEM. The connection point between the riser and PLEM is assumed to be fixed to the seabed.

2.2.1. Bending stiffener

Due to the influence of vessel motions and the wave load, excessive bending curvature occurs at the connection point to the turret, to prevent the bending curvature of the flexible riser at connection point from exceeding the design range, a bending stiffener is generally conducted here. The bending stiffener can not effectively limit the bending curvature, but also increases the fatigue life of flexible pipe. In this paper, the bending stiffener is used to avoid the excessive bending curvature, bending stiffener is shown in figure 4 [15].

Figure 4. Bending Stiffener and bend stiffener schematic



phase [3]

2.2.2. Static Analysis

The first part of the analysis of a flexible riser configuration is static analysis. The loads considered in the static analysis are weight, buoyancy, vessel offset and current load [16].

In OrcaFlex Static equilibrium is determined in a series of iterative stages [14]:

- At the beginning of the calculation, the positions of the vessels and buoys will be determined by the data.
- The static equilibrium for each line will be calculated; the line ends should be fixed or connected to a buoy or vessel.
- The out of balance on each free body (node, buoy, etc.) will be calculated and a new position for the body will be estimated. This process will be repeated until the out of balance load on each is close to zero (include some tolerances)

2.2.3. Dynamic Analysis

After static analysis the next stage in the design procedure is to perform dynamic analyses of the system to assess the global dynamic response. The objective of performing this analysis is to predict the lifetime maximum that is the extreme response of the flexible riser system. These load cases combine different wave and current conditions, vessel positions and motions, riser content conditions to provide an overall assessment of riser suitability in operation and extreme environmental condition [16].

The equation of motion OrcaFlex solves is [16]:

$$M(p,a) + C(p,v) + K(p) = F(p,v,t) \qquad (1)$$

Where in Eq. (1) M stands for inertia load, C stands for system damping load, K stands for system stiffness load, F stands for external load, p, a, v stands for position, acceleration, velocity vector respectively and t stands for simulation time.

2.2.4. Vessel Displacement

Response amplitude operators (RAOs) show the behavior of the vessel in waves with different periods. The RAOs depend on the size, mass, wave and period of waves. RAOs could be separated into rotation and translation. The rotational part includes roll, yaw, and pitch. The translation part includes heave, surge, and sway. The most important ones are heave and roll motions [3].

Each displacement RAO consists of pairs of numbers that define vessel response to a specific wave direction and period. The pair of numbers are amplitude and phase. The amplitude parameter relates to the amplitude of the vessel to the amplitude of the wave. Phase parameter defines the time of vessel motion relate to the wave [14].

There are many conventions to define RAOs. The OrcaFlex Convention is to use the amplitude of response (in length for translation movements or Degree for rotational movements) per unit wave amplitude. Also, use phase lag from the time wave crest passes the RAO origin until the maximum positive excursion is reached [16]. Mathematically we can say:

$$X = A.RAO.Cos(\omega t + \psi) \qquad (2)$$

Where in Eq. (2) X stands for vessel response, A stands for wave amplitude, RAO stands for response amplitude operator, ω stands for wave frequency (rad/s), T stands for time and ψ stands for response phase angle.

2.2.5. Validation

The results obtained using the finite element models in this paper are compared with finite element models in Gurung [11], to validate the way of modelling. Fig 5,6 compares the results of the finite element model and finite element models in Gurung [11].

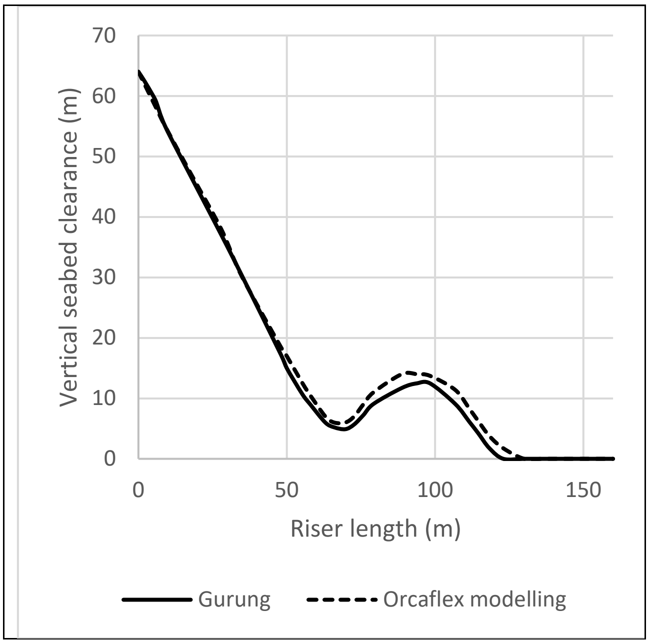


Figure 5. Comparision for riser shape in still water condition between Gurung [11] models and Orcaflex modelling

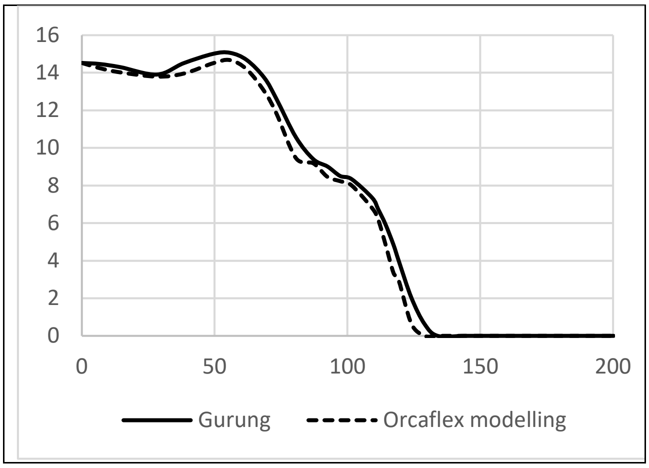


Figure 6. Comparision for maximum riser lateral excursions during lateral loading between Gurung [11] models and Orcaflex modelling

As shown in the figures above the minimum seabed clearance for Gurung [11] model is about 5m and for orcaflex modeling is about 6m and also maximum lateral excursion for Gurung [11] model is 15m and in orcaflex modeling is about 14.5m. The difference between the results are may because of the lack of information about the FSO data and the buoyancy modules data. The results shows a good agreement with the results in Gurung [11] so the way of the modeling is validated

2.3. Load Case

The load cases used for static and dynamic analysis are as table 1 [3], [17]:

Table 1. Load cases used for static and dynamic analysis

Row	Service condition	Vessel condition	Vessel offset	Marine growth	Riser condition
1	Operating	Ballast	Far	0%	Empty
2			Near	50%	Operating
3		Loaded	Cross	100%	flooded

As shown in table 1 a total of 54 load cases are available for static and dynamic analysis. For static analysis used a 100-year current and for dynamic analysis used a 100-year wave and current. When the FSU getting away toward the Plem it's called far condition, when the FSU getting close towards the Plem it's called the near condition and when the FSU transverse moved toward the Plem it's called cross condition.

2.4. Case Study

The khalije fars FSU properties and environmental data for Persian Gulf and also riser specifications are provided by iranian offshore oil company and are as tables 2-4.

Table 2. Khalije fars FSU properties

Title	Unit	Value		
Length overall	*m*	334.67		
Breadth	*m*	60		
Depth	*m*	33		
Vessel condition	-	Ballast	Loaded	
Weight	*ton*	139114.4	405175	
Draught	*m*	8.35	23.75	
Offset	-	Far	Near	Cross
Vessel offset	*m*	13.6	11.5	17.2

Table 3. Persian Gulf environmental data

-	Wave		Current	Wind
Parameter	Height(m)	Period(s)	Velocity(m/s)	Velocity(m/s)
Far	2.9	7.4	0.27	18.6
Near	2.9	7.4	0.27	18.6
Cross	5.4	10.2	0.72	26

The wave and current and wind are assumed in the same direction for each load case.

Table 4. Riser specification

Parameter	Unit	Value
Length	*m*	195
Inner diameter	*mm*	381
Outer diameter	*mm*	491.1
Weight in air	*kg*	217.87
Minimum bending radius	*m*	4.75
Bending stiffness	kN/m^2	432.12
Axial stiffness	10^6N	151.51
Torsional stiffness	$10^8Nm^2/Rad$	0.23

Drag chain data and oil characteristics are as table 5-6:

Table 5. Drag chain data

Chain no	Riser length chain attached to(m)	Chain length(m)	Chain weight(Kg/m)
1	78	59	135
2	90	60	140
3	102	60	145
4	153	54	500

Table 6. Oil characteristics

Parameter	Unit	Value
Maximum crude specific gravity	*API*	16
Design pressure	*barg*	50
Normal operating temp	*c*	38
Design temperature	*c*	60

Marine growth thickness is about 20mm and assumes to be constant in riser length, and also the water depth is 45m.

3. Results

By considering the load case in table 1and using data in tables 2-6, the static and dynamic analysis results for lazy wave and pliant wave and WAW configuration for the riser connected to the turret moored FSU are shown in figures 7-14 as below:
The riser positions in empty and flooded conditions are shown in figure 7 and 8 respectively.

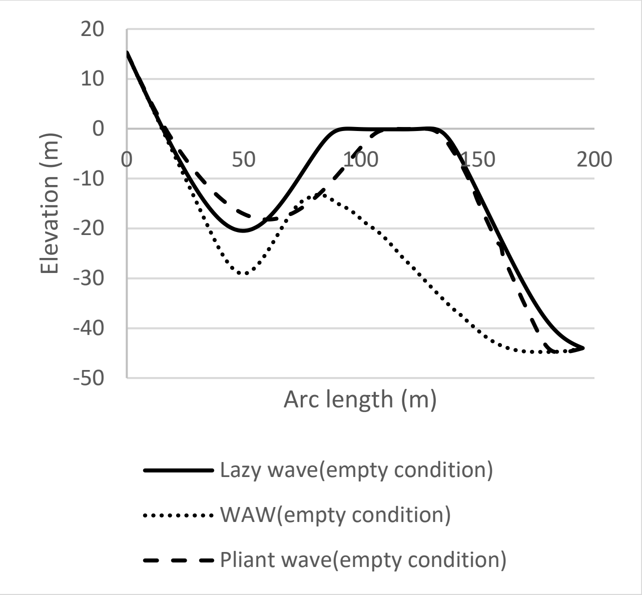


Figure 7. Riser static position for three configurations in empty condition

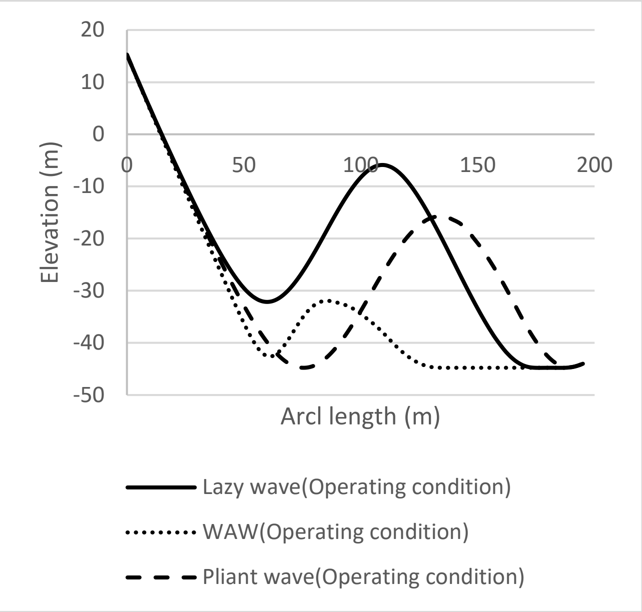


Figure 8. Riser static position for three configurations in operating condition

Corresponding to API-17J the riser should not float on the sea surface or have clashed with vessel keel, and also the riser should not have clashed with seabed in its hog bend area. As shown in figures above the lazy wave and pliant wave configurations are floated on sea surface in empty condition because of that the riser contents is empty and the acting force in downward z-axis is reduced and the uplift force is still available so the uplift force becomes greater than the resistance force (weight forces) so the riser is become flooded on sea surface, when the riser floats on the sea surface the wave effect increases and it reduces fatigue life of riser, and also the risk of clash with other riser and fast boat increases. In the other side the drag chains in WAW configuration helps the riser to make equilibrium between the weight and buoyancy force and prevents the riser from floating on sea surface. Also, the pliant wave configuration in the operating condition has clashed with the seabed and it increases the stress range in the clash zone and reduces the fatigue life of flexible riser. The WAW configuration has a 4.5m clearance with the seabed and it helps the riser to operate in a safe condition and not to have clashed with seabed due to floater displacement.

The riser dynamic tension in empty and flooded condition for these three configurations are shown in figure 9 and 10 respecitvely.

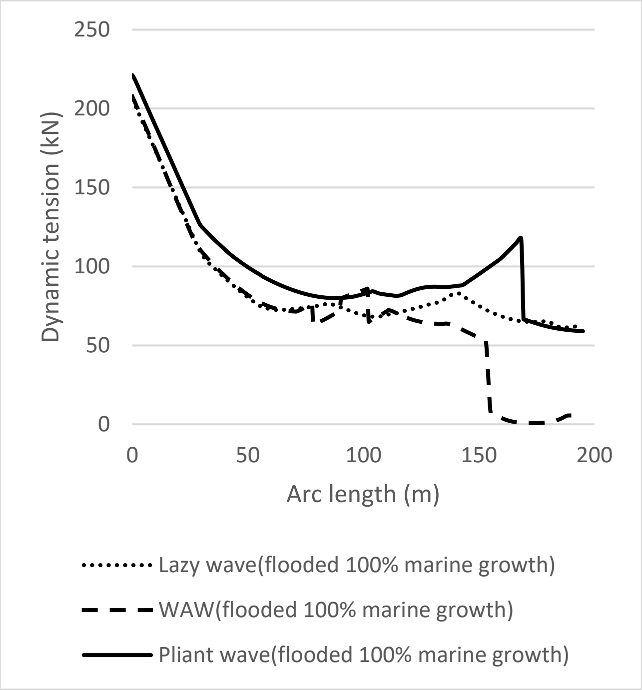


Figure 9. Riser dynamic tension in a flooded condition for the vessel in far offset

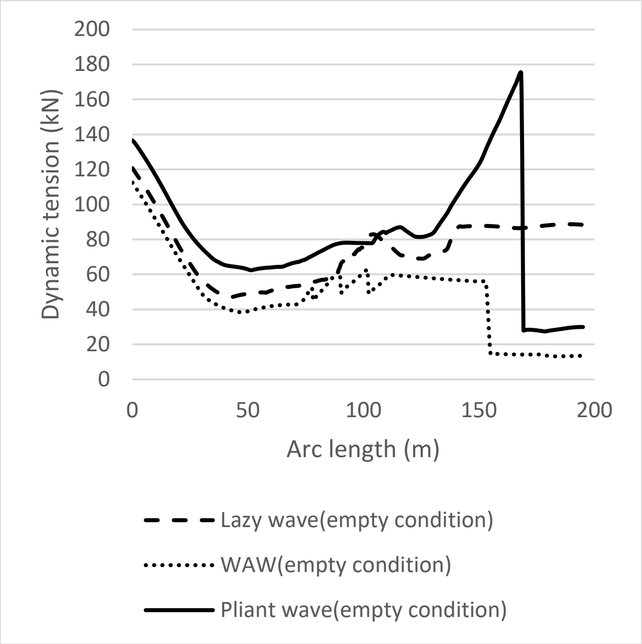


Figure 10. Riser dynamic tension in empty condition for the vessel in the far offset

The maximum tension force in riser happens when the vessel is in Far condition, as shown in figures 9-10 the maximum tension force in the connection point between the riser and PLEM is created when the riser is empty, and the maximum tension force in this point between this three configurations happens in lazy wave configuration (85kN), with accordance to API 17B and API 17J the tension force in the connection point between the riser and PLEM should be as minimum as possible and tend to zero, in pliant wave and lazy wave configuration tension in riser and PLEM connection point are 30kN and 85kN in empty condition respectively and also 58kN in flooded condition and that's too high for this point, in the other side the tension at this point in WAW configuration is 13.5kN that is an acceptable value. In the WAW configuration the stabilization chain helps the riser to limit the riser elevation and also limit the riser displacement so the tension in PLEM connection point is decreas. For the pliant wave configuration the tension at the point of 160m in riser length is increasing because of that in this point the riser is tethered to seabed and the tension is increased in this connection point. For the WAW configuration at the point 155m of riser length the tension is decreasing because of existence of a drag chain that helps the riser to reduce the displacement and also sustain the loads that caused by vessel displacement. Also, the maximum tension in riser length happens in the connection point between riser and turret and it's due to riser hanging weights and also contents weight, for these three configurations is about 210kN in flooded condition and it is less than the allowable tension for the riser.

The riser normalized curvature is shown if figure 11.

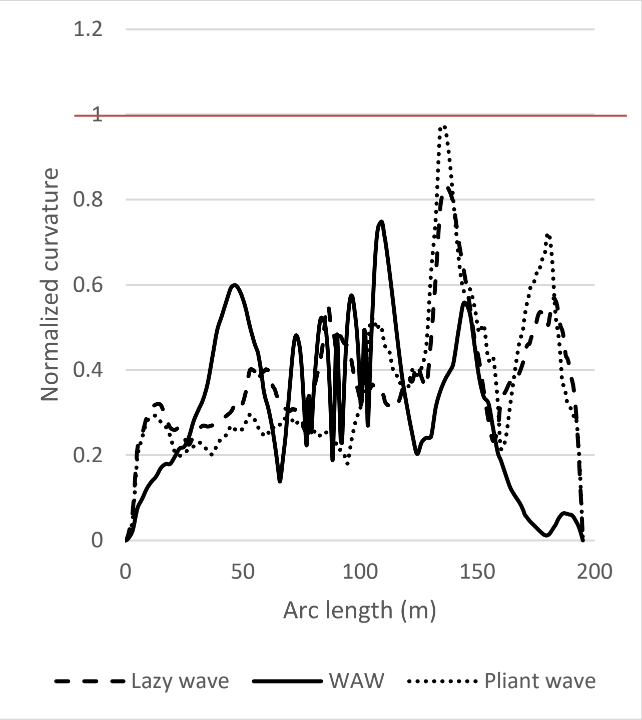


Figure 11. Riser configurations normalized curvature

Based on API-Rp-17J the bending radius of riser should be higher than the minimum bending radius. If the normalized curvature value for the riser is close to one then the bending radius of that riser is small and close to the allowable bending radius of the riser. As shown in figure above for the pliant wave configuration the value of the normalized curvature is close to one and it is not suitable, as shown in figure above the WAW configuration has the least normalized curvature value among these three configurations, so its bending radius is smaller than the other two and it causes the riser to experience less bending moment in comparison with the other two.

the maximum normalized curvature for lazy wave and pliant configurations occur at the end of buoyancy section and touch down point. For the WAW configuration maximum normalized curvature occur before the buoyancy section, and it occurs because of that to observe the minimum seabed and sea surface criteria, the buoyancy section is being closed to hang-off length so the radius of hog bend area is reduced then the normalized curvature in this area increased.

The riser configurations lateral displacement are shown in figure 12.

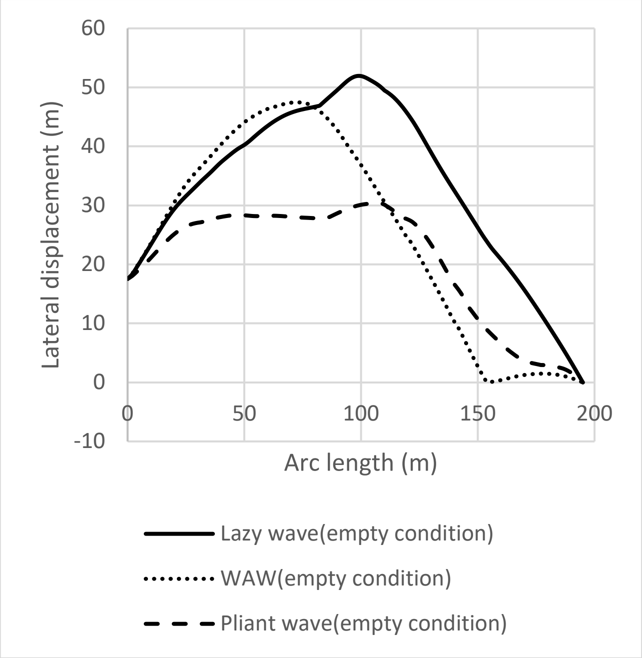


Figure 12. Riser configurations lateral displacement in the operational condition for the vessel cross offset

As shown in figure above the pliant wave configuration because of the existence of a tether has the least lateral displacement among these three configurations and it reduces the probability of riser clashing with other facilities underwater, the WAW configuration has less lateral displacement than lazy wave configuration and also the lateral displacement for WAW configuration in TDZ is smaller than the other two configurations and it helps the riser to reduce the risk of clashing with other facilities on the seabed.

The risers line clearance by assuming two lines of riser connected to a turret with 2 m clearance at the hang-off and riser connection point are shown in figure 13.

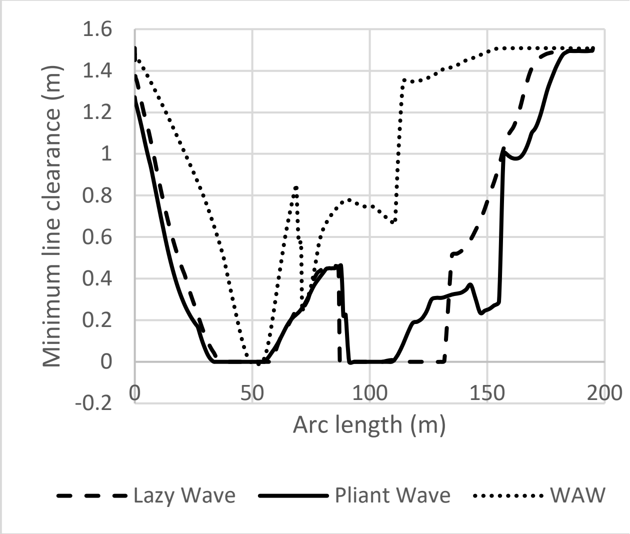


Figure 13. Riser configurations line clearance with two lines of 15 inches riser in cross condition

When the two or more risers are connected to a turret, the riser interference based on DNV-RP-C203 should be evaluated. The line interference is assessed in three categories:

- No clashing: The lines do not touch each other although they may very close to each other.
- Allowable clashing: The allowable clashing define as clashing occurs in the bare part of the riser (not buoyancy section), the clash force should be evaluated.
- Imposible clashing: The clashing occurs in the buoyant section of at least one line

As shown in figure 13 when the lazy wave and pliant wave configurations cannot be used in the system of risers in shallow water because of that the risers with these configurations has clash in their buoyant section with other risers. The WAW configuration only have clash in its bare part so the clash force for this configuration should be evaluated. The clash force for WAW configuration is shown in figure14.

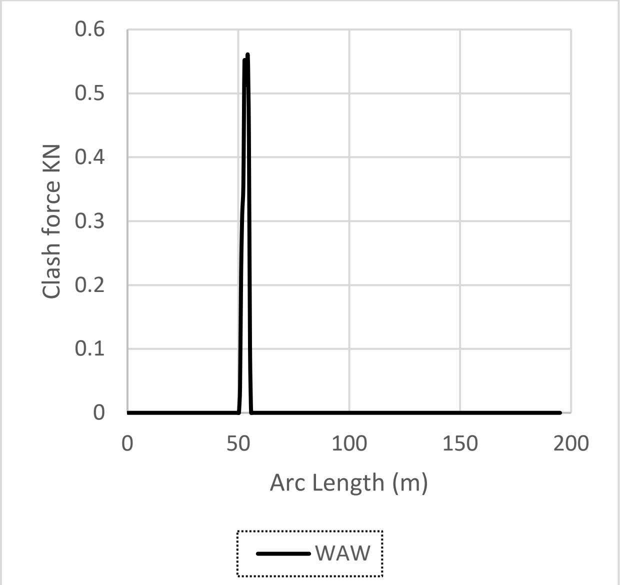


Figure 14. WAW configuration clash force for the two line of 15 inches riser in cross condition

As shown in figure above the clash force between the bare parts of two risers for WAW configuration is small, so by using this configuration with a system of risers, there is no clashing problem can be observed.

4. Conclusion

In this paper, firstly the available configuration for a flexible riser in shallow water is investigated then the static and dynamic analysis for the 15 inches riser in the 45m water depth for the lazy wave and pliant wave and weight added wave configuration are performed and it is concluded that:

- Lazy wave configuration for the riser in shallow water with high internal diameter has plent of limitation and one of those limitations is inability of this configuration to make clearance with sea surface. Also the high tension force in the connection point between the riser and PLEM is another limitation of this configuration.
- Pliant wave configuration in addition to the limitation of lazy wave configuration has another limitation like low bending radius compared with other configurations. Also this configuration has clashed with seabed in hog bend area.
- Weight added wave configuration has better performance against the challenges which exist in shallow water. The minimum sea surface clearance for this configuration is about 12m and seabed clearance about 4.5m and it helps the riser to operate in a safe condition. Also the maximum tension in PLEM connection is about 6.5kN in operating condition and it shows that the tension at this point is reduced about 89% compared with two other configurations. The minimum bending radius for WAW configuration is about 6.78m and it is increased about 29% compared with pliant wave configuration and is increased about 15% compared with lazy wave configuration.
- In the case that the system of risers are connected to the turret the WAW configuration has better performance in compared with two other configurations.

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