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A Comparison of the Dynamic Response of a Product Transfer System in CALM and SALM Oil Terminals in Operational and Non-Operational Modes in the Persian Gulf region

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ABSTRACT

Offshore oil terminals are a cheaper and safer solution than conventional shore terminals for unloading and loading tankers. There are several types of offshore terminals, including Catenary Anchor Leg Mooring (CALM) and Single Anchor Leg Mooring (SALM). Product transfer systems, including floating and underwater pipes, are the most important components of these terminals. The present study aims to compare the dynamic response of a product transfer system in these two models of offshore oil terminals. To obtain structural responses, including forces created in floating and underwater pipes, a simulation in Orcaflex software is used considering wind, current, and wave forces in different sea states. The curvature and tension in the pipes are considered a criterion for evaluating the failure modes. The results show that under operating conditions, the curvature and effective tension of the pipes in the SALM terminal are 5% and 93% lower than those in similar operating and environmental conditions in the CALM terminal, respectively. As the environmental conditions increase up to Sea State 8, when the tanker is not connected to the terminal, the SALM terminal pipes will have more structural stability and usability, while the CALM terminal pipes will only have stability up to Sea State 6. The tensions generated in the pipeline end manifold (PLEM) of the SALM terminal are also lower than those in the CALM terminal. It is also observed that the critical point for the CALM terminal pipes is the connection point to the terminal buoy, while it is the connection point to the seabed for SALM terminal pipes, which should be considered in designing a product transfer system for this type of terminals.

1. Introduction

One of the most important components of the production and supply chain of hydrocarbon products in the oil industry is the transfer of these products. This type of transfer is generally performed by two pipelines to the consumption points, as well as by oil terminals and loading tankers (Shuttle Tankers). Oil terminals are also divided into shore and offshore groups[1]. In shore oil terminals, the tanker must be moored at the shore for loading and unloading operations. However, in offshore terminals, petroleum products are transported to a safe area far from the shore using pipelines, and after transferring these products to offshore terminals, the tanker is loaded. So, this system does not need complex mooring compared to the shore terminals. Therefore, the tendency has increased towards the use of offshore terminals due to the high costs of the construction and maintenance of shore terminals, including dredging operations, on the one hand and the risks of unloading and loading operations (due to the possibility of the proximity of these terminals with industrial centers or some residential on the beach) on the other hand. The use of offshore terminals with the possibility of unloading and loading oil tanker in places far from the shore and close to the oil field will reduce the cost of piping at sea over long distances. It will also be safer as the high-risk operations of transporting petroleum products to tankers are transferred to points far from the shoreline, residential areas, and facilities located on the shore.

Offshore oil terminals are divided into different types according to how the tanker is controlled and how petroleum products are transferred, so choosing the best option for these types of oil terminals should be commensurate with the water depth, tanker dimensions and tonnage, the product to be transferred, dynamic interaction behavior of buoy and tanker, and other operational considerations. This paper investigates two common types of these terminals, including CALM and SALM. One of the most important parts of these terminals is the transmission system, which is responsible for transporting the product from the seabed to the tanker and must be designed in such a way that the transfer is provided safely and in accordance with the rule. Therefore, recognizing the effective parameters and examining the intensity of their impact on the transmission system is of particular importance in the study and design of these two common offshore terminals. Investigating and comparing the structural response of product transfer systems in these terminals is one of the most important criteria for selecting the appropriate type of oil terminal.

Several research studies have been done to investigate the product transfer system in oil terminals. The first flexible pipes (Known as hoses) for oil terminal were used in Libya in 1969. Accordingly, researchers began to study the behavior of hose systems. The hose of CALM oil terminals was studied by Ziccardi [2]. In this study, two riser configuration models including Chinese lantern and Lazy-S configuration were investigated. Brady and et al. examined the forces generated in the hoses using a statistical method that led to the further study of the hoses connected to the CALM terminal in the following years [3]. In 2013, Eiken addressed different configurations of underwater cravings (Lazy-S and free-hanging) with different diameters and showed what criteria and challenges should be met in designing these structures [4]. Qi and et al. examined the skirt (bottom of the terminal) of a CALM structure and performed a feasibility study on a riser with a Chinese lantern configuration. They showed that by increasing the diameter of this body, the mass was increased in the direction of heave and roll, which reduced the displacement of the structure in the heave direction. The feasibility of using this type of riser configuration for specific areas of the installation of this terminal has also been subject to studies[5]. Amaechi and et al. explored the resistance of a CALM riser with a Chinese lantern configuration connected to a tanker under different environmental conditions. In this study, Ansys Aqwa software was used for the hydrodynamic analysis of the CALM buoy, and Orcaflex software was used for the analysis of the riser. The study aimed to determine the effect of flow angle parameters on the behavior of the riser structures, such as curvature, effective tension, and bending moment[6]. The interaction between the mooring system and the riser in vessels is an important parameter that has been subject to extensive research in recent years[7]–[9]. Karegar explored different types of flexible riser configurations for shallow water. Dynamic modeling and analysis were performed using the OrcaFlex software package to obtain the structural responses The paper enumerates the main challenges for shallow water with harsh environments for flexible ridges, including MBR, large vessel offset, clearance, and Marin growth [10]. In 2014, Pecher examined two types of mooring system configurations, including CALM and SALM connected to a wave energy converter and studied the effect of stiffness and size of mooring lines on the displacement of the structure, as well as the effect on the tension of these mooring lines [11].

According to previous studies, the amount of tension and bending force in these systems is one of the most important criteria for examining and comparing different cases. Since the main component of oil terminals is the product transfer system, the comparison of these systems helps in choosing the right oil terminal. This study models the floating and underwater hoses of two terminals including the CALM and SALM with relevant specifications under the environmental conditions of the Persian Gulf and compares their responses. Also, to check the stability of these systems, they are examined with increasing environmental conditions when the tanker is not connected. Also, according to previous studies, the product transfer system of these terminals has not been examined for general analysis under real operating conditions.

1.1 Transfer product system in CALM and SALM oil terminals

One of the most common types of offshore terminals is the CALM structure, which consists of a cylindrical body connected to the seabed by 4 to 6 mooring lines. This buoy consists of two parts, an upper and a lower part. The lower part is in the water. The buoyancy of the buoy is created by the buoyant force on this part, which is restrained to the seabed by a mooring line. The upper part of the buoy is connected to the lower part by a bearing system, which allows 360-degree rotation. The tanker is connected to the top of the buoy with a hawser, which allows the tanker to rotate. This type of terminal whose application dates back to 1959 is the most commonly used system for the transfer of oil products compared to other offshore terminals.

According to Figure 1, to transfer the product from the seabed to the tankers in this system, the products are first transferred to a buoy by underwater pipes. Then, floating pipes are used to transfer them to the tanker. The underwater pipes in this type of terminal are the boundary between PLEM on the seabed and the hang-off point in the buoy, which are divided into three configurations, including a Chinese lantern, lazy S, and steep S. In these configurations, buoyancy modules are used to gain the appropriate shape. The floating pipes are connected to the underwater pipes using a SWIVEL system located in the buoy. The SWIVEL system allows these pipes to rotate relative to each other. Before unloading and loading, the floating pipes are afloat on the surface of the water, but then after the tanker is moored, the end of these pipes is connected to the tanker manifold by a crane. The floating pipes and underwater pipes are made of smaller parts, which are usually made in lengths of 9.1 meters, 10.7 meters, and 12.2 meters. So, these smaller parts are connected to each other to get the required length.

The SALM structure is connected to the seabed only by one mooring line as shown in Figure 1. Due to the universal connections in the mooring line of this structure, the tanker can rotate 360 degrees around this buoy. When the hawser (the connection cable between the tanker and the buoy) is under high stress, the buoy can go underwater or when it hits the tanker, it can go under the tanker without any problem. One or two hawsers are used to connect the tanker to the terminal, and unlike the previous structure in which petroleum products are transported from the seabed first to the terminal and then to the tanker, in this case, the products are directly transferred from the seabed to the tanker. One of the most important components of this structure is the swivel system located on the seabed. Due to the fact that the swivel system of the SALM terminal is located on the seabed, less force is applied to it than the swivel terminal CALM, which is located inside the buoy and on the surface of the water. The SALM terminal was first used in 1969 and is the second most used system after CALM in the transport of petroleum products from the seabed to tankers in offshore operations.

(a) (b)

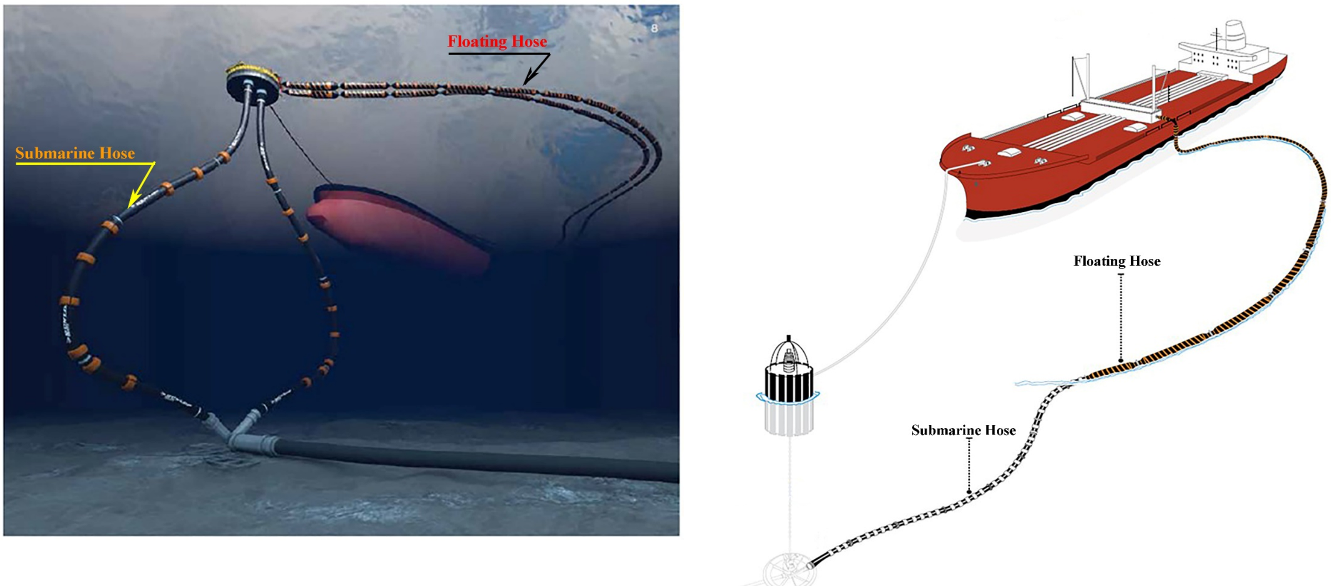


Figure 1. A schematic view of the product transfer;
(a): SALM terminal, (b): CALM Terminal

1.2 Hose material

Flexible pipes generally combine low bending stiffness with high axial stiffness, which is achieved by making the pipe in different layers. Flexible pipes are composed of different layers. Each of these layers is responsible for withstanding a specific force (tension, bending, torsion, etc.). The connection of these layers by a vulcanization process to form a single pipe is basically called a hose or bonded pipe and is used in oil terminals as shown in

Fig. 2. The other alternative is the Unbonded pipe, which is used to transfer the product in structures such as FSU, FPSO, etc.

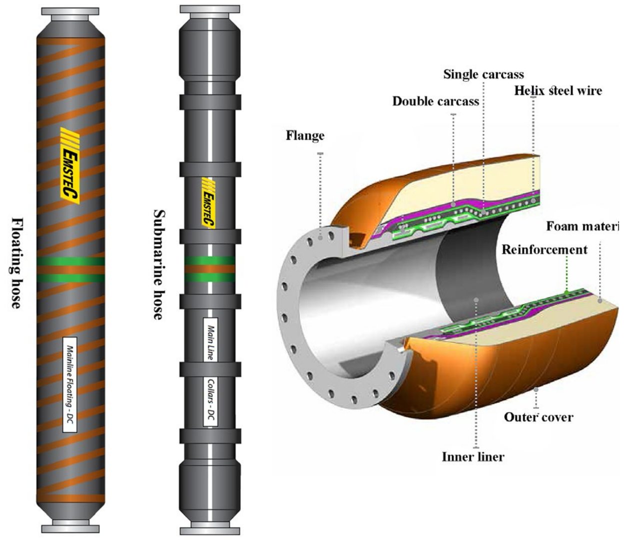


Figure 2. Double carcass hose dimensions and main components.

Hoses are essentially made in lengths of 9.1, 10.7, and 12.2 meters, which should be connected to each other to achieve the required length. The two ends of a hose have a flange in that the different pipes are connected to each other by stud bolts and nuts. The innermost part of the pipe is made of NBR rubber, which is responsible for sealing and tightens the flanges to the pipe. Reinforcement is made of polyester and withstand the internal pressure of the pipe as well as excessive loads and stresses and are adjusted according to operating and environmental conditions. For better environmental conditions and better resistance to effective tension, high external pressure, or severe bending anchors, helix steel wire reinforcement is incorporated in the hose body structure. The carcass is an interconnected metal layer that provides resistance to pipe collapse. The double carcass is used for situations that require high burst resistance. Figure 3 shows a schematic view of this flexible pipe layer.

2. Numerical modelling

To investigate the dynamic response of the product transfer system in oil terminals under the operating conditions of unloading and loading, as well as the environmental conditions, the numerical model of the terminal structure in interaction with the tanker was used in Ansys Aqwa and OrcaFlex software packages. The modeling process is presented in Figure 4. According to this process, the geometry of the terminal and the tanker connected to it should be first simulated in Ansys Aqwa software and then, the outputs should be fed into Orcaflex software to analyze the interaction of the terminal and the tankers in real operating conditions.

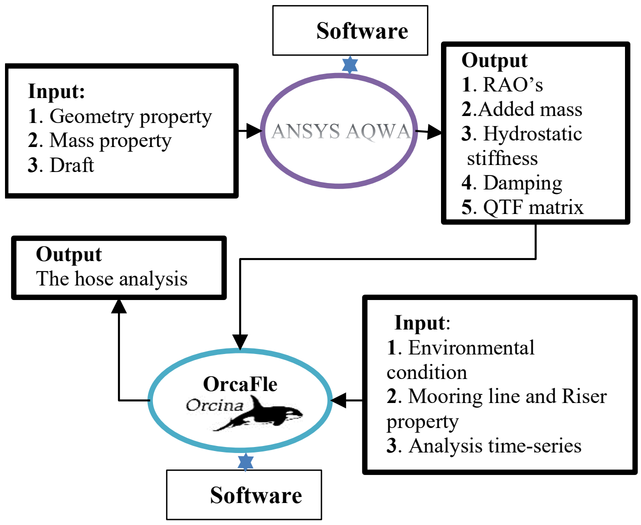


Figure 3. The designing process in the software.

As shown in Figure 4, the inputs of Ansys Aqwa include water depth and the geometrical specifications, mass characteristics, and draft of the terminal and the tanker. The outputs include RAO, mass matrix, Hydrostatic stiffness matrix, Damping and QTF matrix in each vessel. These outputs are transferred to Orcaflex software. The structural responses of each structure are calculated by creating coupled models from each terminal as a connection to the tanker and according to the type of mooring system and environmental conditions. The equation of motion of each object on the horizontal plane is described in Equation 1.

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F(t)\} \qquad (1)$$

in which [M], [C] and [K] are the mass, damping, and stiffness matrices, respectively, {X} is the displacement vector, and F(t) is the force vector. The mass of the structure is assumed to be concentrated in any degree of freedom. The added mass due to the water surrounding the structural components is also considered to be Ma.

2.1 Finite Element Model

The finite element model in Orcaflex software [12] includes parameter modeling of pipe, mooring line, and vessel. OrcaFlex analyzes structures statically and dynamically including boundary conditions such as buoy, vessels, etc., and models the finite elements of lines. In this software, mooring lines and pipes are specified as lines. As shown in Figure 4 Orcaflex uses a finite element model for the lines. The lines are divided into a set of segments that are bounded by straight massless segments at each end of the node. The segment model only models the axial and torsional properties of the line. Other properties (mass, weight, buoyancy, etc.) are all focused on the nodes.

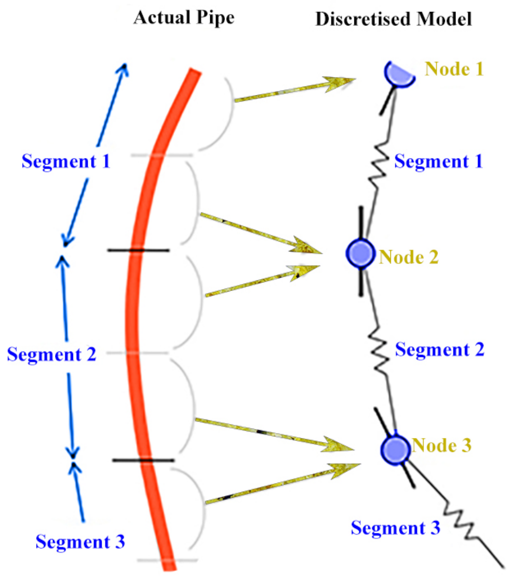


Figure 4. The OrcaFlex line element.

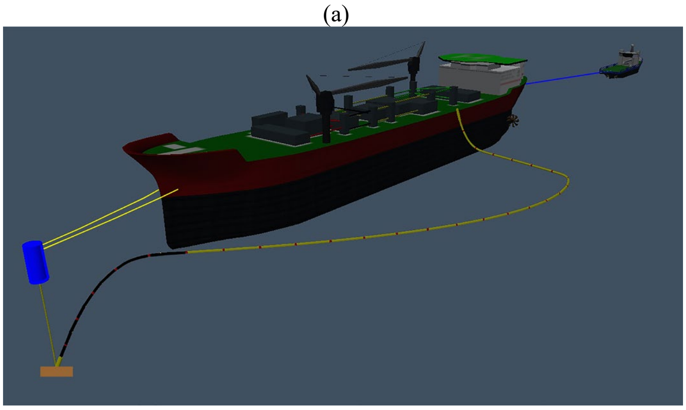
Models built in Orcaflex software for SALM and CALM are shown in Figure 5.

3. Case Study

3.1 Buoys

Geometric characteristics and effective parameters used in modeling the studied floating oil terminals and tankers in this paper are presented in Tables 1 and 2. The modeling process of these vessels, as shown in the flowchart diagram of Figure 1, begins with the mass, geometric and water characteristics of each vessel in ANSYS AQWA software, and the results of this analysis include the characteristics of static response and the dynamics of floating structures that are introduced in Orcaflex software as rigid body characteristics with six degrees of freedom as a terminal and tanker floating model. To compare the effect of offshore terminal type on the response of transport system structures, the paper calculates the characteristics of the CALM structure according to the actual sample of the terminal built in the Persian Gulf and the characteristics of SALM structure according to the structure built in the Gulf of Mexico for the highest tonnage of the tanker connected to it. The metacentric height is considered a criterion for evaluating the stability of the modeled buoys. For all these buoys, this parameter is greater than one, so both terminals will be stable. The buoy of the CALM terminal is composed of two components connected by a joint so that if the tanker rotates, the upper part of the terminal also rotates. A schematic view of the buoys is shown in Figure 6.

(a)



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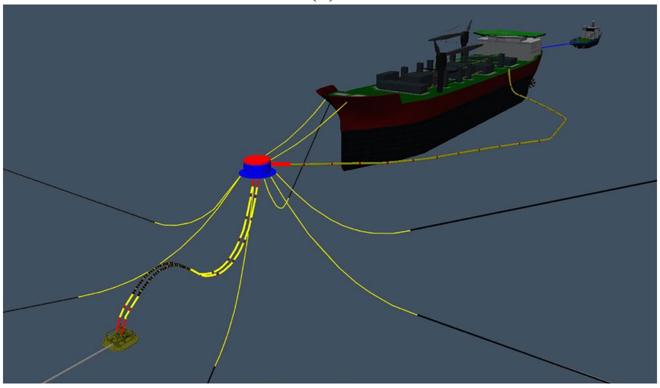


Figure 5. Modeling oil terminals in Orcaflex software; (a): SALM system, (b): CALM system

Table1. Specifications the vessels modelled in the study.

Parameters	Unit	CALM	SALM	Tanker
			Value	
Draft	m	3.266	9	22.6
Center of gravity (X-direction)	m	0	0	170.18
Center of gravity (Y-direction)	m	0	0	0
Center of gravity (Z-direction)	m	-0.766	6	17.3
Moment of inertia(X-direction)	$kg \cdot m2$	4840000	6244000	8.260E+10
Moment of inertia(X-direction)	$kg \cdot m2$	4840000	6244000	2.35E+12
Moment of inertia(X-direction)	$kg \cdot m2$	9350000	2890000	2.35E+12
Diameter	m	12.5	6.4	
Diameter of skirt	m	16.63	-	
Weight	ton	289.98	400	
Height	m	5.3	14	
Length between perpendicular, L_{BP}	[m]	-		320
Breadth molded, B	[m]	-		60
Depth, D	[m]	-		30.5
Windage area, A_L (longitudinal),surge area	[m^2]	29.53	32	1155.25
Windage area, A_T (Transverse),sway area	[m^2]	29.53	32	3693.81
Windage area, A_T*L_{BP},yaw area	[m^3]	369.12	204.8	1.182E6
Displacement	[kg]	-		3.6712E+08

3.2 Mooring line

To moor the buoy of the CALM terminal on the seabed, six moorings made of studless chains are modeled as linear elastics and their bending and torsional effects are assumed to be negligible. Each of these chains with a length of 380 meters is placed in a circular position on the periphery of the sea. The C_d and C_M coefficients are considered constant for all mooring lines during analysis and the amount of pretension in each morning is equal. In the SALM terminal, a stud mooring is used to control the buoy. This type of structure also makes the buoy rotatable due to the type of chain connections, which is a universal connection. To simulate this feature in Orcaflex software for two ends of the mooring, one in the seabed and the other connected to the buoy, zero bending stiffness and torsion are considered which allows free rotation at both ends of the mooring. General specifications and parameters required for the modeling of the mooring are given in Table 2.

Table 2. Specifications of the mooring line.

Parameters	Unit	CALM	SALM
		Value	
Diameter	**mm**	95	175
Length	**m**	380	38.8
Weight	**Kg/m**	180	671
Axial stiffness	**kN**	712000	3093000
Minimum breaking load	**kN**	8180	25173
C_d	**-**	1.2	1.2
C_M	**-**	1	1

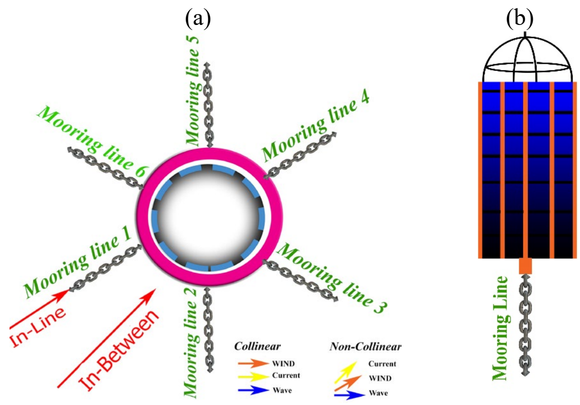


Figure 6. The arrangement of the mooring line; (a): CALM system, (b): SALM system

In this study, to connect the tanker to the terminal, two hawsers have been used for each terminal buoy, which is nonlinearly modeled in Figure 7. The length of these hawsers is 60.96 m and their maximum allowable tension (MBL) is 5800 kN

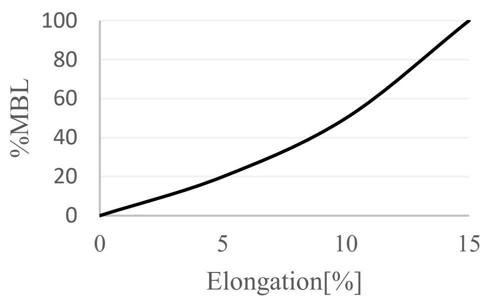


Figure 7. The non-linear axial stiffness in the hawser system.

3.3 Hose

In the CALM terminal, underwater hoses are created in the Lazy S configuration, as shown in Figure 8. These hoses are 117.7 m long, which are created by 11 parts of a 10.7 m hose section. The upper end of the pipe is fixed to the lower part of the buoy, and the lower end of the pipe is fixed to the seabed at a certain angle to the horizon. Bending stiffeners are used at both ends due to the high bending force that is created. Since both ends of each part have a flange made of steel, in models, both ends of the pipe section are assumed to be made of flanges made of steel according to the profile shown in Figure 4. To obtain the desired configuration shape, buoyancy modules are used along the length. The floating pipes in this terminal are modeled with 23 pipe sections with flanges at each end. One end of the pipe is connected to the tanker at a height of 15 m above the sea level, and the other end to the revolving part of the terminal (upper part of buoy).

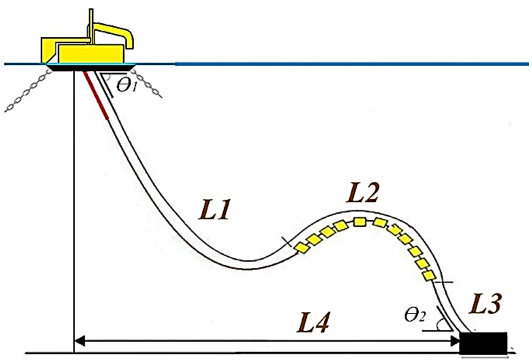


Figure 8. Submarine Hose Design Parameter.

The boundary conditions for the pipes used in the SALM terminal are such that the end connected to the seabed must rotate freely and the other end is fixed connected to the tanker. The pipe used consists of two parts, floating and underwater, which are connected to each other, each with a length of 362 meters, creating an integrated pipe. A buoyancy module is used to create a proper riser configuration. The specifications required for the design of floating and submarine pipes for each terminal are given in Table 3.

3.4 Loading

The first step in the analysis and design process is to determine the load and forces on the structures under study. The forces acting on these structures include forces from waves, winds, and currents. The combination of these forces also has a significant impact on the total incoming forces. Due to the wave phenomenon, two important forces of drag and inertia are created on the structure so that all the forces created by the wave are the result of these two forces. The drag force of F_D is affected by the velocity of the fluid, which depends on the shape and roughness of the body, the Reynolds number, and the intensity of the turbulence in the flow. The inertial force F_I is caused by the acceleration of the fluid particles (water). Due to the windage surface of the upper part of the tanker, the wind force is of great importance. This force is due to the change in pressure created in the free wind flow and is a function of wind speed, direction, surface, and shape of structural members. The current force also increases the drag and lifts force in the submerged parts of the structures, which is able to change the wave height and period in interaction with the wave(DNV-RP-C205, 2010).

Table 3. The physical and mechanical properties of the hose.

ITEM	Transfer system for CALM terminal		Transfer system for SALM terminal	
	Submarine hose	Floating hose	Submarine hose	Floating hose
Section length [m]	10.7	12.2	12.2	12.2
Inner diameter [mm]	500	0.609	609	609
Total length L [m]	118	298	48.8	314
Outside diameter [mm]	620	1117	1117	1117
Bend stiffness [kNm^2]	158	300	500	300
Tension stiffness [kN]	4325.866	4325.866	4325.866	4325.866
Weight (empty)[kg/m]	434	600	439	600
Minimum breaking tension [kN]	810	810	810	810
Fluid density [kg/m3]	725	725	725	725
Drag force coefficient, C_d	0.9	0.9	0.9	0.9
Added mass coefficient C_m	1	1	1	1
Water depth, [m]	47.8	47.8	47.8	47.8
MBR	4*ID	6*ID	4*ID	6*ID

Wave Load

Morrison equation is used to calculate the wave force in slender components, such as mooring and risers, and diffraction theory is used for components whose body dimensions are larger than the wavelength, such as buoys. The transverse and rotational displacements in the vessel are calculated by RAO using Equation 2 for each wave height and period[14].

$$X = A.RAO.\cos(\omega t + \psi) \quad (2)$$

in which X is the response of the structure, A is the amplitude of the wave, and Ψ and ω are the angle of the frequency flow and the frequency of the wave, respectively. Given the research site, the wave spectrum used in this study is the modified Jonswap spectrum which is appropriate to the environmental conditions of the Persian Gulf. It is presented in Equation 3, (DNV-OS-E301, 2010).

$$S(\omega) = \frac{\alpha g^2 \gamma^{\alpha}}{\omega^5} \exp\left(-\frac{5}{4}\frac{\omega_p^4}{\omega^4}\right) \quad (3)$$

in which g is a gravitational constant, and the key parameters for defining this spectrum include the characteristic wave height Hs, spectral peak period, Tp, and the peak enhancement factor γ, which are presented in Table 5 for this study. To compare three terminals in the same conditions, a wave direction of 30 degrees relative to the direction of the tanker is considered.

Wind and Current

In addition to the force on the structure due to the wave phenomenon, the forces arising from the two phenomena of wind and current are also of special importance. The parameters used to calculate wind force and current are presented in Table 5. The direction of wind force and current parallel to the wave force used in calculating the most critical displacement of the tanker connected to the terminal is considered as per the profile of two wind forces and constant current in accordance with the OCIMF regulations[16].

This paper considers the environmental conditions including wave, current, and wind in accordance with the operating conditions of the Persian Gulf as expressed in Table 4 to investigate the dynamic behavior of floating structures and their impact on the pipe system. In all conditions, wind, wave, and current directions are considered to compare the response of these terminals.

Table 4. Environmental conditions.

Parameter				**value**	**unit**
Wave	JONSWAP	Operation	H_s	2.6	[m]
			T_p	7.5	[s]
			γ	1.4933	-
		Survival	H_s	3.9	[m]
			T_p	8.5	[s]
			γ	2.2261	-
Wind	Constant velocity	Operation		22	[m/s]
		Survival		26	[m/s]
	Air density			1.28	[kg/m^3]
Current	Triangular profile	Operation	surface	0.7	[m/s]
			seabed	0	[m/s]
		Survival	surface	0.8	[m/s]
			seabed	0	[m/s]
Sea	Water depth			47.8	[m]
	Water density			1025	[kg/m^3]

In order to evaluate the stability of floating and underwater desires hoses against the applied forces when the tanker is not connected and no operation is performed, in addition to the operating conditions of the Persian Gulf, four other environmental conditions are considered according to Table 5. These environmental conditions include waves with a characteristic height of 2 to 5.5 meters.

Table 5. Different types of sea states.

Sea state *i*	**H_s**	**T_p**	**γ**	**Wind velocity[m/s]**
Sea State 5	2	5.5	1.4933	10.28
Sea State 6	3	7	1.4933	13.37
Sea State 7	4	8.5	2.2261	16.69
Sea State 8	5.5	9.7	2.2261	20.57

The density of the Jonswap wave spectrum is calculated by Equation 3 and plotted in Figure 9 for different environmental conditions. Since for each environmental condition, the wind speed must be in accordance with its wave height, so in Table 5, the corresponding wind speed is also given for each wave height.

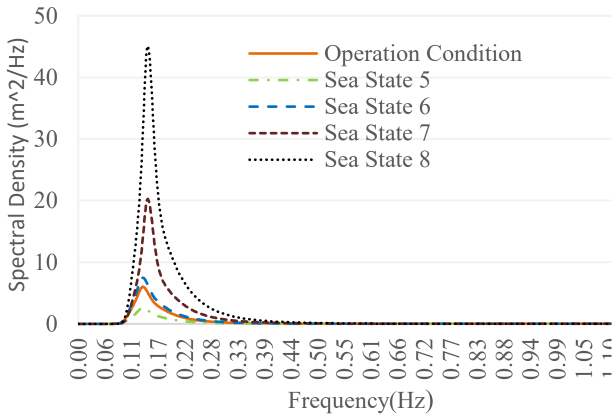


Figure 9. The spectral density for different sea states

4. Failure mode for Hose

Possible failure modes for pipes include tension failure, excessive bending, collision, and fatigue(API, 2008). This study omits the fatigue failure mode. For tension failure mode, the maximum tension should not exceed the allowable tension (F <Fmax) where F is the maximum tension created along the pipes and Fmax is the maximum allowable tension declared by the manufacturer. The critical location for this mode of failure usually occurs at the beginning and end of the pipes. Another mode of failure for the pipes is excessive bending, which is checked by the curvature and bending moment criteria. The amount of curvature and bending moment along the pipe should not exceed the allowed values. Permissible values are calculated by Eq. (4) and (5).

$$\text{Allowable curvature} = 1/\text{MBR} \tag{4}$$

$$\text{Allowable Bending moment} = \frac{\text{Bend Stiffness}}{\text{MBR}} \tag{5}$$

in which MBR is declared by the manufacturer, which is equal to 6 and 4 times the inner diameter of the pipe for floating and underwater pipes, respectively. Also, according to the collision criteria, the pipes should not have any contact with other facilities and the seabed.

It is certainly more useful to normalize the outputs and show curves of results for non-dimensional parameters. Therefore, to show the results related to tension and curvature, this results are normalized, so that these values are divided by their allowable value and are introduced as normalized tension and normalized curvature. Allowable values for tension and curvature for floating hoses are 810 kN and 0.27 rad/m, respectively. Also for submarine hoses the allowable tension and curvature are 810 kN and 0.33 rad/m, respectively.

5. Results

Product transfer systems in CALM and SALM terminals are considered the most important component of the terminal. Therefore, the amount of forces created in these systems can help a lot in choosing the best type of oil terminal in a certain area. This paper examined the product transfer system in two terminals, CALM and SALM. The results are as follows.

The amount of tension created in floating and underwater pipes is one of the most important failure criteria to study the behavior of pipe in CALM and SALM terminals as a variable. First, the environmental conditions are considered according to the operating conditions of the Persian Gulf. The results obtained in this step are shown in Figure 10.

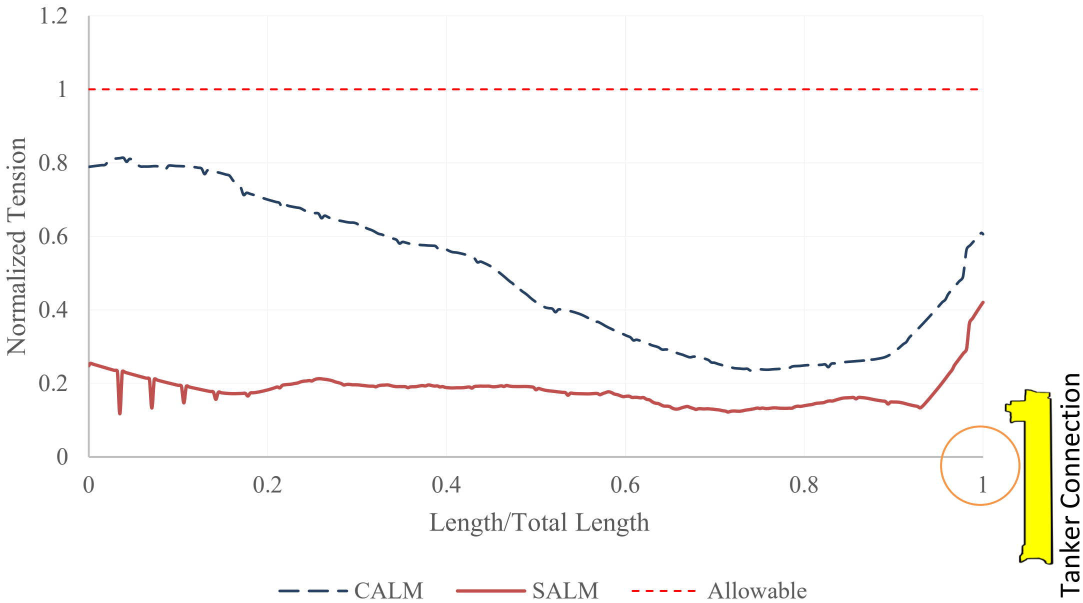


Figure 10. The effective tension in the hose of CALM and SALM oil terminals

The results show that in each terminal, the maximum amount of effective tension occurs at the beginning and end of the pipe. However, the effective tension under operating conditions does not exceed the allowable value in the two terminals. In the CALM terminal, the critical point for effective tension is the connection point of the pipe to the terminal buoy. But, in the SALM terminal, the maximum tension occurs at the connection point of the pipe to the tanker. The maximum effective tension for the CALM and SALM terminal pipe is 658 and 340 kN, respectively.

Another criterion of failure in examining pipe behavior is curvature. Figure 11 displays the amount of curvature along the pipe for the CALM and SALM terminals.

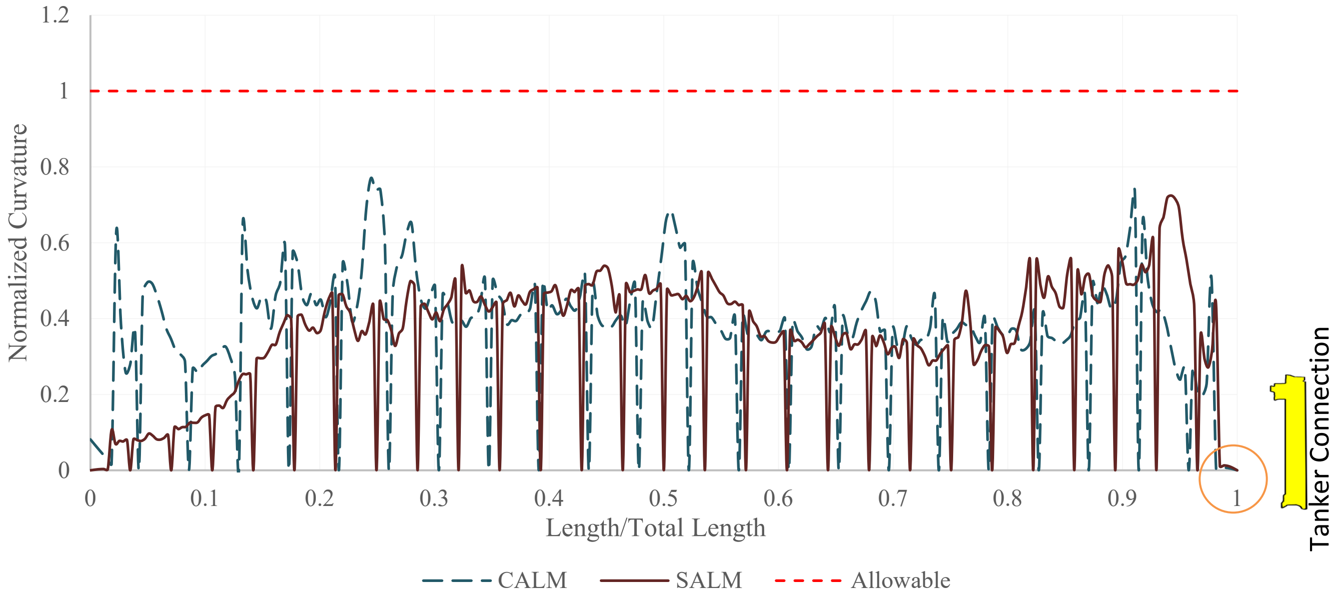
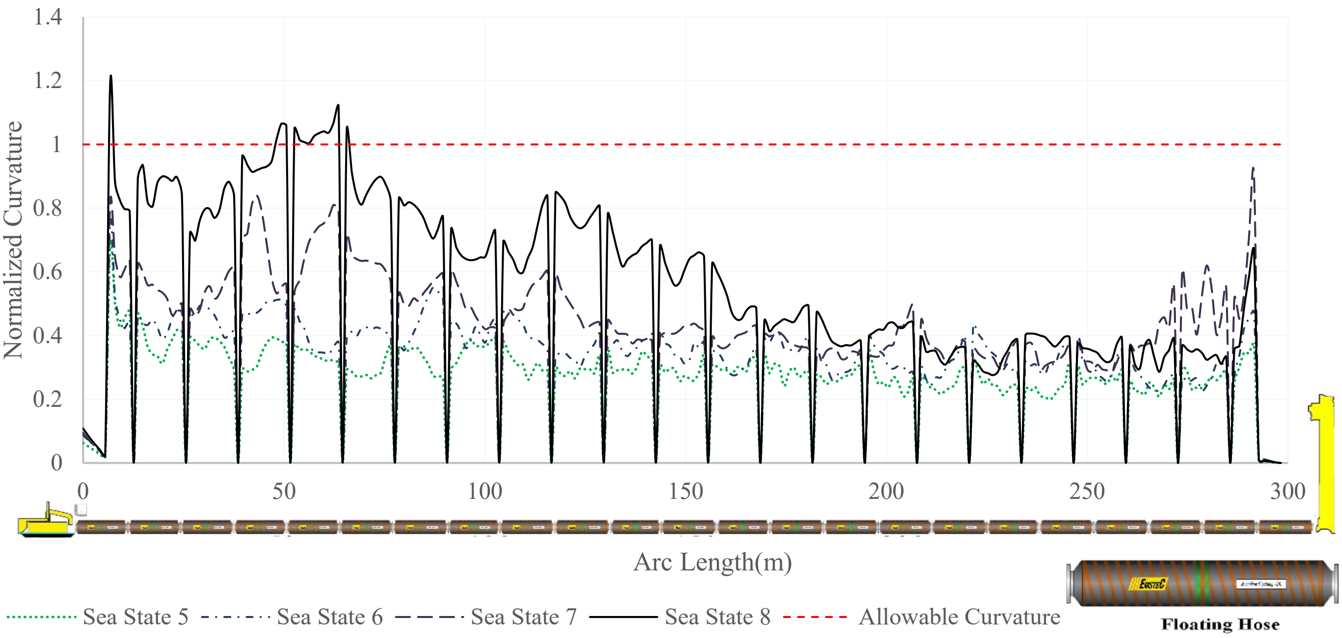


Figure 11. The curvature in the hose of CALM and SALM oil terminals, (a) CALM Terminal, (b) SALM Terminal.

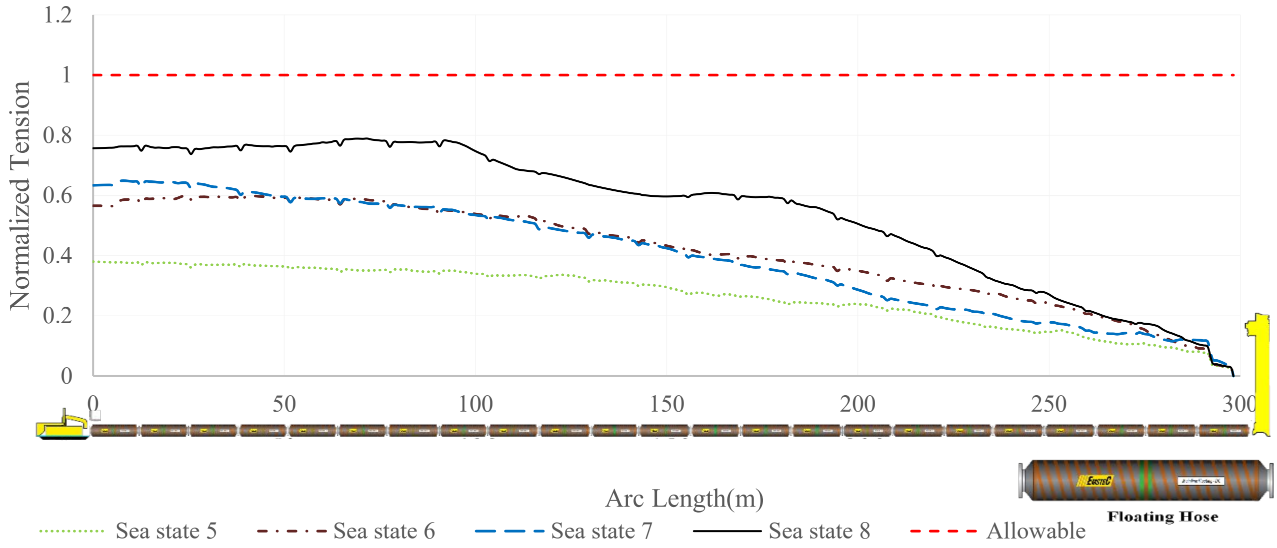
The results show that the amount of curvature along the pipe for the two terminals did not exceed the allowable value. According to Figure 8, since the pipes are connected with different lengths and these different lengths are connected by a flange, the amount of curvature at these points is zero. In the SALM terminal pipe, the amount of curvature in the PLEM part is almost negligible, and the maximum value occurs near the connection to the tanker. In the SALM and CALM terminals, the maximum curvatures along the pipe are 0.21 and 0.2, respectively.

Another thing that should be considered to check the product transfer system in these terminals is the condition that the tanker is not connected and no operation is performed. It is, therefore, necessary to study the stability of these systems under different environmental conditions. In the CALM terminal, when the tanker is not connected, there are floating pipes on the water surface, one end of which is free and the other is connected to the terminal body. The ends of the underwater pipes in these terminals are also connected to the seabed and the buoy. The environmental conditions are increased up to Sea State 8 to determine how the behavior of these systems changes with increasing environmental conditions. The results obtained for the CALM terminal are shown in Figure 12.

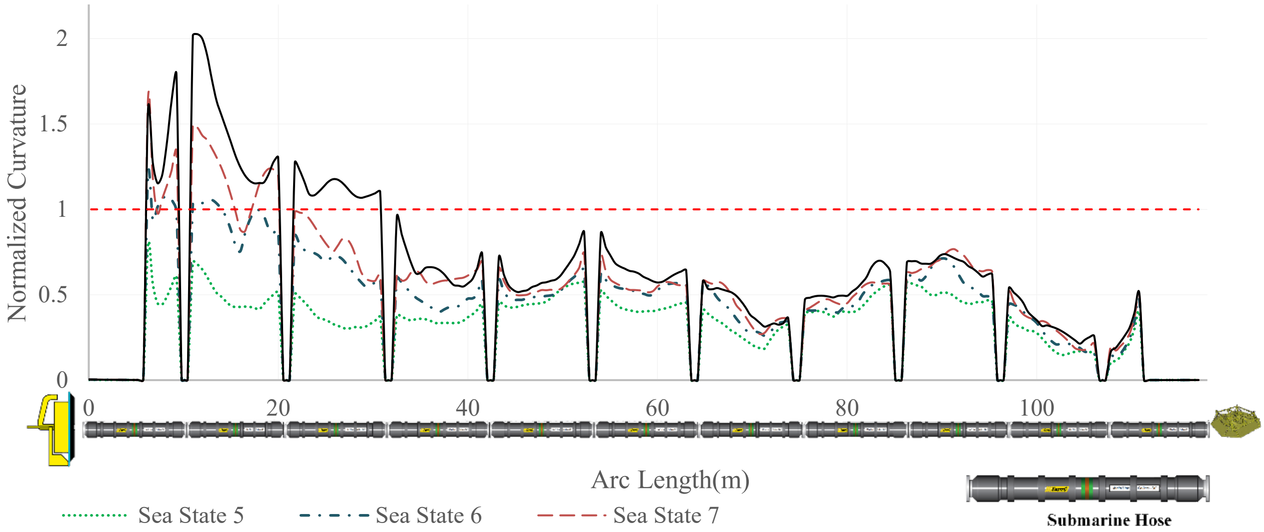
(a)



(b)



(c)



(d)

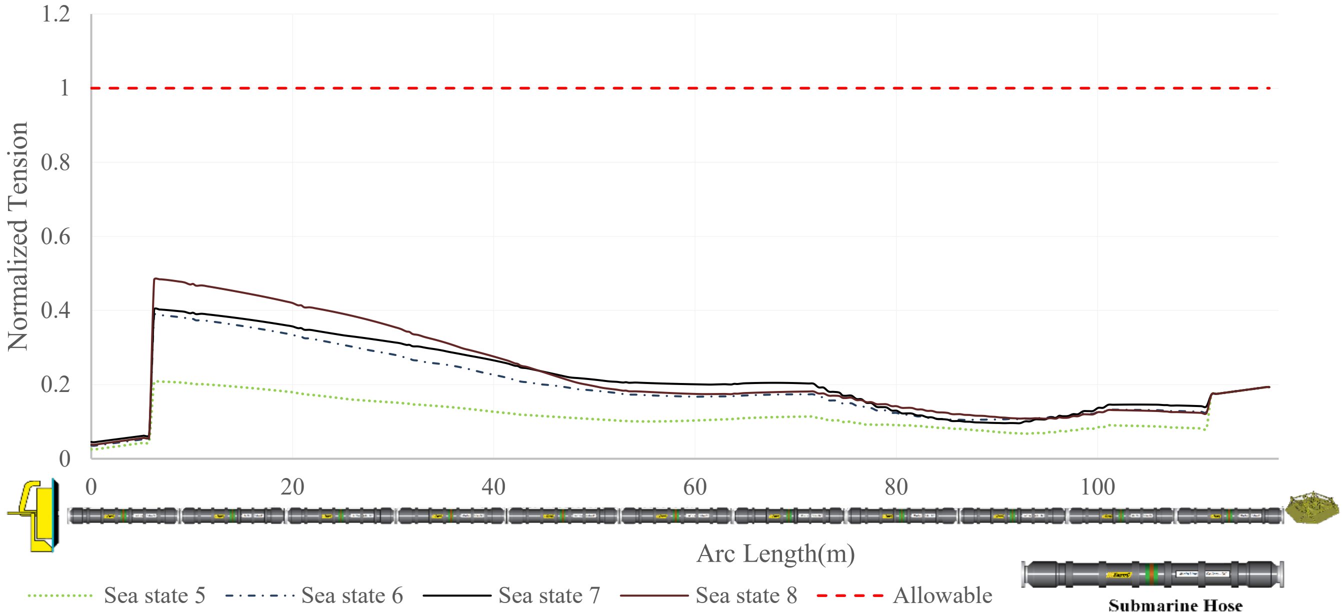
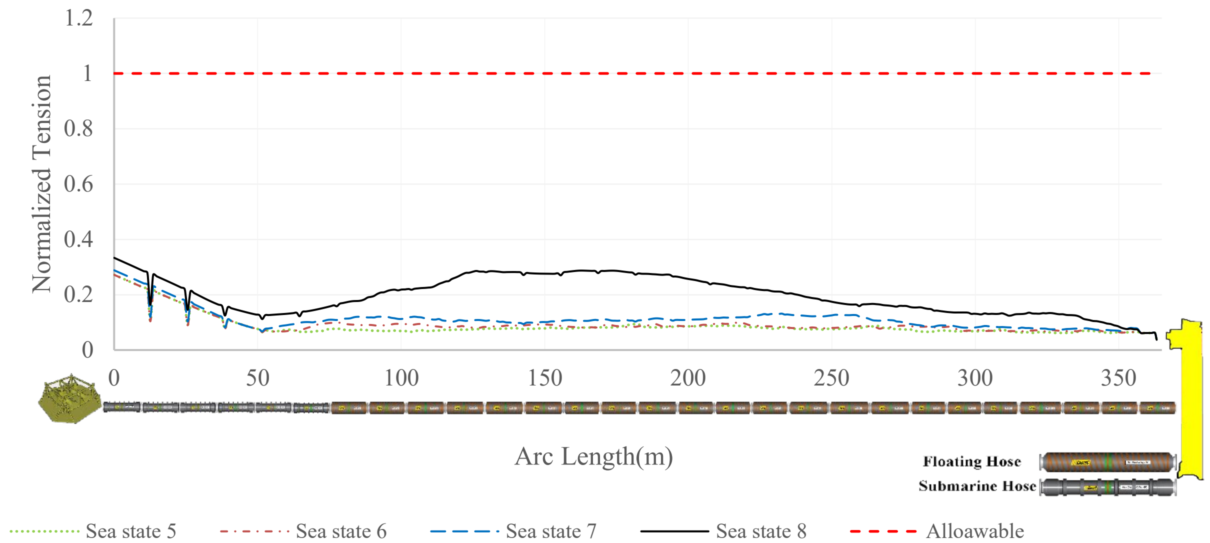


Figure 12. The curvature and effective tension generated in the CALM hose under different sea states; (a): The Curvature of floating hose, (b): The Curvature of submarine hose, (c): The Effective tension of floating hose, (d): The Effective tension of submarine hose.

The criterion for studying the response of marine terminal pipes is curvature and tension. The results show that by increasing the environmental conditions to Sea State 6, none of the mentioned criteria are violated, and the terminal can last until these environmental conditions without a tanker connected. But from Sea State 6 onward, the curvature criterion is violated, so it will not have the necessary stability. This is while the effective tension criterion has not exceeded the allowable value up to Sea State 8. It is also observed that the critical location in this terminal with the increase in environmental conditions is the point at which the pipe (floating and underwater) is connected to the buoy.

Unlike the CALM terminal that consists of two separate floating and submarine pipes, product transfer systems in the SALM terminal is composed of floating and submersible pipes that are connected to one another and a single pipe. As the environmental conditions increase to Sea State 8, results are obtained that are shown in Figure 13.

(a)



(b)

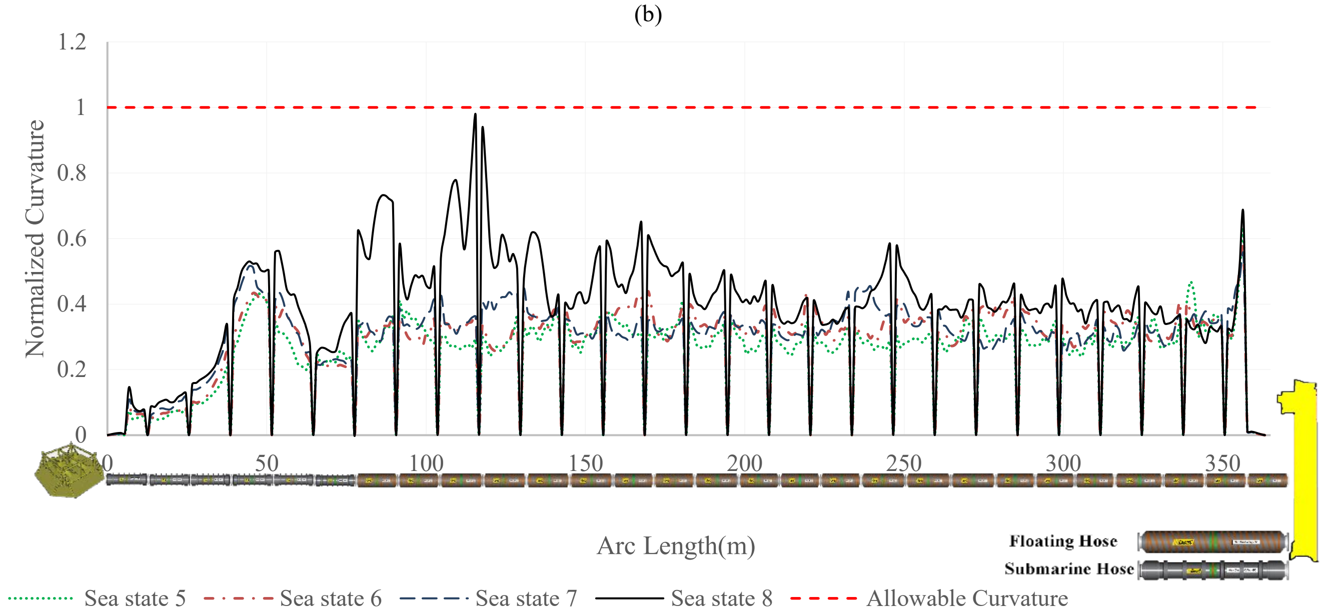


Figure 13. The curvature and effective tension generated in the SALM hose under different sea states; (a): Effective tension, (b): Curvature.

The results reveal that by increasing the environmental conditions to Sea State 8, none of the criteria of curvature and tension for the pipes of this terminal will be violated.

The forces created at the lower end of the pipes (PLEM), connected to the seabed, in the SALM and CALM terminals are of special importance due to the presence of facilities on the seabed. When the terminals are in operating conditions, the forces will be generated in the PLEM section as shown in Figure 14.

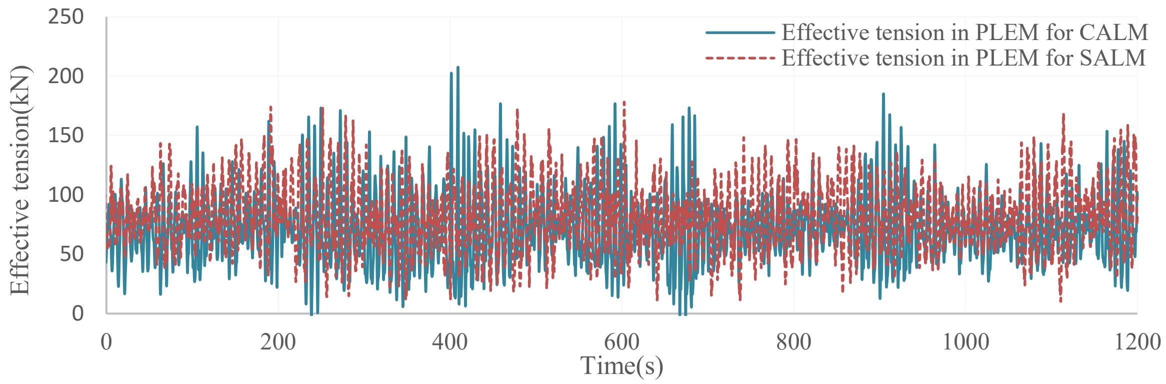


Figure 14. The effective tension generated in PLEM of the CALM and SALM hose under operational conditions.

Based on the results, the time history of the tension created in the PLEM part is lower in the SALM terminal. The maximum tension generated for the CALM and SALM terminals is 207 and 178 kN, respectively.

6. Conclusion

This study investigated the product transfer system, including submarine and floating pipes, in CALM and SALM terminals. First, the response of these systems was examined under the operating conditions of the Persian Gulf. In the next step, the stability of these systems was evaluated under different environmental conditions (up to Sea State 8) when no tanker was connected. The results are summarized below.

- Under the operating conditions of the Persian Gulf, the tension force and the curvature in the SALM terminal product transfer system are created to a lesser extent. The results show that under operating conditions, the curvature and effective tension of the pipes in the SALM terminal are 5% and 93% lower than those in similar operating and environmental conditions in the CALM terminal, respectively.
- With increasing environmental conditions, the product transfer system in the SALM terminal shows more stability when no operation is performed so that this system can be used even for Sea State 8. However, the product transfer system in the CALM terminal can be used for areas whose maximum environmental conditions are in line with Sea State 6.
- The tensions created in the PLEM section in the SALM terminal are 14% less than the tensions created in the CALM terminal.
- The critical point of the product transfer system for the CALM terminal is the connection point of the pipe to the terminal buoy, where the most displacement occurs. But, in the SALM terminal, the critical point for the effective tension of the seabed and for the curvature is the area where the pipe comes out of the water.

List of Symbols

PLEM	Pipe Line End Manifold
CALM	Catenary Anchor Leg Mooring
SALM	Single Anchor Leg Mooring
MBR	Minimum Bending Radius
FSU	Floating Storage Unit
DNV	Det Norske Veritas
API	American Petroleum Institute
OCIMF	Oil Companies International Marine Forum
FPSO	Floating Production Storage and Offloading
RAO	Response Amplitude Operator
QTF	Quadratic Transfer Function

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