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Parametric Study on the Behavior of An Innovative Subsurface Tension Leg Platform in Ultra-Deep Water

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Abstract

This study focuses on a new technology of Subsurface Tension Leg Platform (STLP), which utilizes the shallow-water rated well completion equipment and technology for the development of large oil and gas fields in ultra-deep water (UDW). Thus, the STLP concept offers attractive advantages over conventional field development concepts. STLP is basically a pre-installed Subsurface Sea-star Platform (SSP), which supports rigid risers and shallow-water rated well completion equipment. The paper details the results of the parametric study on the behavior of STLP at a water depth of 3000 m. At first, a general description of the STLP configuration and working principle is introduced. Then, the numerical models for the global analysis of the STLP in waves and current are presented. After that, extensive parametric studies are carried out with regarding to SSP/tethers system analysis, global dynamic analysis and riser interference analysis. Critical points are addressed on the mooring pattern and riser arrangement under the influence of ocean current, to ensure that the requirements on SSP stability and riser interference are well satisfied. Finally, conclusions and discussions are made. The results indicate that STLP is a competitive well and riser solution in up to 3000 m water depth for offshore petroleum production.

Key words: subsurface tension leg platform, parametric study, global behavior, ultra-deep water

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1 Introduction

Oil and gas fields in UDW are currently developed by using dry or wet trees, or a combination of both. However, it is recognized that both dry tree and subsea tree development concepts have drawbacks, and especially in the present days, petroleum exploration of offshore fields proceeds into water depth close to 3000 m at a relatively high cost while the oil prices stay low. Table 1 illustrates the benefits and limitations of subsea and dry tree developments.

Thus, new concepts of offshore production systems are needed to meet the demanding challenges presented by large water depth and harsh environment in UDW. In this context, hybrid riser concept (Hatton et al., 2002; Tellier and Thethi, 2009) seems to be an attractive alternative. Normally, a hybrid riser consists of a vertical bundle of steel pipes upwardly tensioned by external buoyancy, and flexible jumpers connecting the top of a vertical riser bundle to a Floating Production Unit (FPU) at the sea surface decoupling the riser bundle from FPU motions. However, the present hybrid riser concepts still belong to subsea field development solution to a large extent, which provides a degree of vessel and field expansion flexibility with simplified riser interface, but at the expense of high work over costs as well as high flow assurance requirement.

Aiming to overcome the demanding limitations of subsea and dry tree developments in UDW, the STLP concept (Huang et al., 2013, 2014; Zhen et al., 2013, 2014) is proposed and can be regarded as the subsurface development for offshore petroleum production. In this paper, the STLP concept and its unique features are introduced first. With this understanding, the numerical models for the global analysis of the STLP in waves and current are presented. Then, extensive parametric studies are carried out with the focus on mooring analysis, riser dynamic analysis and riser interference analysis. Critical points are addressed on the mooring pattern and riser arrangement under the influence of ocean current. Finally, conclusions and discussions are made for this novel concept.

2 STLP concept

2.1 STLP configuration

STLP primarily consists of three parts: SSP, rigid risers and subsurface well completion (SWC) equipment, as shown in Fig. 1.

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Table 1 Features of subsea vs. dry tree developments (Lim, 2009)

Feature	Dry tree development	Subsea development
Drilling cost	From facility	Requires MODU
OPEX cost	From facility	Requires MODU
Facilities CAPEX cost	High cost hull	Choose least cost hull
Offshore construction	Heavy lift requirements	Depends on riser system
Development flexibility	Restricted due to hull form	Minimal vessel impact
Riser/vessel interfaces	Complex interaction	Simpler interaction
Vessel flexibility	Restricted to Spar or TLP	Full range
Shut in location	In well bay close to people	Seabed isolation and offset
Flow assurance	Shortest flow path	Potentially long tie flowlines

Note: the gray grids illustrate the limitations of subsea and dry tree developments.

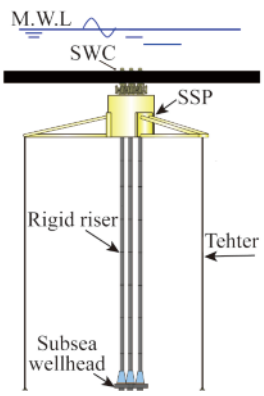

Fig. 1. Sketch of STLP.

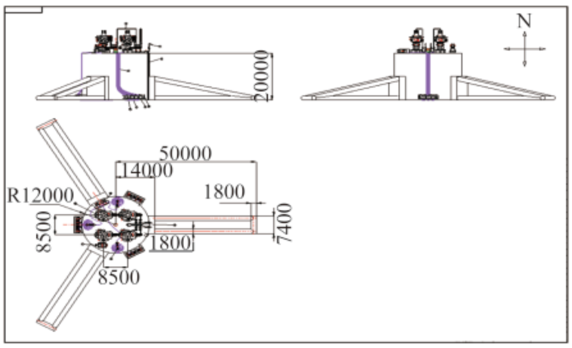

Fig. 2. SSP dimensions and overall layout (unit: mm).

The SSP provides a stable subsurface working platform, which supports rigid risers as well as the SWC equipment. It is located 200 m below Mean Water Level (M.W.L) in the present design to minimize direct wave loading and ocean surface current effects. The Sea-star hull design features a single column with three cantilevering trusses radiating outwards at the base. Three cantilevering trusses are the critical feature of the Sea-star structure, which are designed to eliminate clashing risks between the tether and the adjacent riser while minimizing the current induced load which it suffers to a large extent. The main dimensions and construction details of the SSP are illustrated in Fig. 2.

The rigid riser is designed to connect the subsea wellhead with the subsurface wellhead which is located at the top of the SSP. The rigid riser is composed of an external casing and one inner production tubing while the tubing conducts the petroleum. The space between these two structures is filled by nitrogen. The detailed properties of the rigid risers are presented in Table 2. It should be noted that the connections between the riser and the subsea wellhead as well as between the riser and the SSP are made by steel tapered stress joints. Besides, a steel keel joint is used to locally stiffen the fatigue critical region of the outer casing between the riser and the keel opening of the SSP. More details regarding the stress joint and keel joint are presented in Table 3. A projection of the rigid risers spread from the SSP to the seabed is shown in Fig. 3. Note that the spacing between neighboring risers at the SSP is primarily driven to provide enough space for the shallow-water rated X-mas trees, whereas the well spacing at the seabed is chosen to avoid clashing. The STLP mooring system consists of three vertically loaded sheathed spiral strand tethers, which are

Table 2 Properties of the rigid riser

Parameter	Symbol	Value	Unit
Number	n	5	–
Casing outer diameter	D_{OD}	0.3239	m
Casing thickness	t_{OD}	0.0191	m
Tubing outer diameter	D_t	0.1397	m
Tubing thickness	t_t	0.0127	m
Equivalent weight in air (empty)	m_e	203.74	kg/m
Top tension factor	TTF	1.7	–
Equivalent axial stiffness	EA	3.776×10^9	N
Equivalent bending stiffness	EI	4.616×10^7	N·m^2

Table 3 Properties of the stress joint and keel joint

Parameter	Length (m)	Initial external diameter (m)	Final external diameter (m)
Top stress joint	5	0.3239	0.3556
Bottom stress joint	20	0.3239	0.5271
Keel joint	11	0.40	0.40
Two tapered element (connecting the riser to the keel joint)	0.5	0.3239	0.40

secured to the seabed by using suction piles. These tethers are pre-tensioned and thus provide SSP's stability from which the installation of the rigid risers and SWC equipment will benefit, and constrains rigid risers to move collectively and ensures the positive separation as well. Table 4 presents the detailed tether properties.

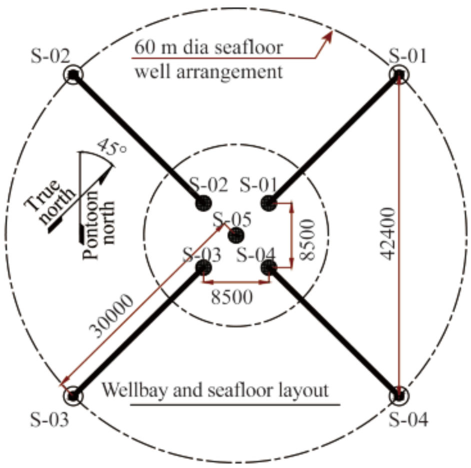

Fig. 3. Plan layout of the STLP riser (unit: mm).

Table 4 Tether properties

Parameter	Symbol	Value	Unit
Number	n	3	–
Nominal diameter	D	0.141	m
Sheathing thickness	t	0.011	m
Nominal weight in air	w	104	kg/m
Axial stiffness	EA	1.817×10^9	N
Minimum breaking load	$M.B.L$	21509	kN
Safety factor	f_s	2.22	–

2.2 How the STLP works?

In the present study, the STLP is aimed to act as the aided subsurface petroleum production and exporting system together with any FPU, including FPSO, semi-submersible platform, TLP and Spar platform. It is assumed that the required subsea wells are pre-drilled. Then, the STLP will be installed and in service at the field site. Finally, the petroleum from the reservoir is transmitted from the STLP to the FPU by means of flexible jumpers, which are in a slack catenary shape to isolate the STLP from the FPU motions. The overall configuration of the STLP with flexible jumpers and the FPU is shown in Fig. 4. In order to reduce the number of flexible jumpers to optimize the interface with the FPU and eliminate the risk of twisting, a functional manifold (Zhen et al., 2014), which is placed at the top of SSP, is designed to make the strings' connection, as shown in Fig. 5.

As noted previously, specific advantages of the STLP concept are offered as follows:

(1) Riser loads on the FPU are substantially reduced.

(2) Field layout is optimized and allows large offshore developments and unforeseen future field expansion, as a large number of risers can be supported.

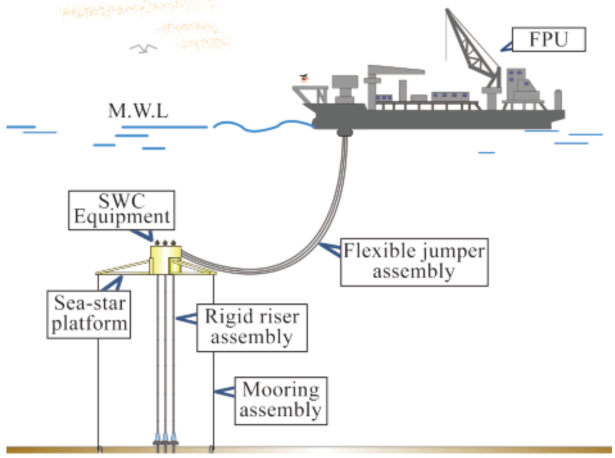

Fig. 4. Sketch of the STLP with flexible jumpers.

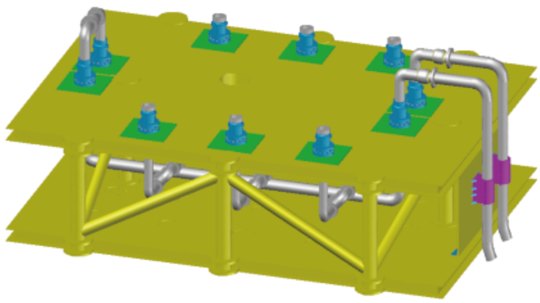

Fig. 5. Sketch of the manifold assembly.

(3) Direct access to local subsea wells is provided, and demanding flow assurance requirements can be met.

(4) In place the riser fatigue is low, as the FPU motions are directly transferred to the flexible jumpers and not to the STLP, which will be subjected to limited direct wave loading since the SSP is submerged away from the wave zones.

(5) New technology of the SWC offers improved technical and commercial performance.

(6) Flexibility of the installation schedule is improved, as the FPU's arrival at the field site is not necessary.

3 Numerical models

3.1 Hydrodynamic loads

In the present study, hydrodynamic loads on the tethers, risers and SSP are calculated by using an extended form of Morison's equation, as shown in follows:

$$F_w = (\Delta_f a_w + C_a \Delta_f a_r) + \frac{1}{2}\rho C_d S V_r |V_r|, \quad (1)$$

where, F_w is the fluid force, Δ_f is the mass of fluid displaced by the body, a_w is the fluid acceleration relative to earth, C_a is the added mass coefficient, a_r is the fluid acceleration relative to the body, ρ is the fluid density, V_r is the fluid velocity relative to the body, C_d is the drag coefficient, and S is the drag area. The term in the parentheses is the inertia force and the other term is the drag force.

3.2 Equation of the coupled motion

The equation of coupled motion for the STLP (SSP, rigid risers, and tethers) is as follows:

$$M(p,a)+C(p,v)+K(p)=F(p,v,t), \tag{2}$$

where, $M(p, a)$ is the system inertia load; $C(p, v)$ is the system damping load; $K(p)$ is the system stiffness load; $F(p, v, t)$ is the external load; p, v, a, and t are the position, velocity, acceleration, and the simulation time, respectively.

3.3 Riser mechanical behavior

The rigid riser can be analyzed as a tensioned beam under the axial tension, lateral loads and the effect of hydrostatic pressures due to internal and external fluids. The governing differential equation (Sparks, 2007) for the riser static behavior undergoing small deflections can be obtained from the balance of forces and moments, as follows:

$$EI\frac{d^4x}{dz^4}-(T_{tw}-p_iA_i+p_eA_e)\frac{d^2x}{dz^2}-(w_t+w_i-w_e)\frac{dx}{dz}-f_{(z)}=0, \tag{3}$$

where EI is the bending stiffness; T_{tw} is the true wall tension; p_i is the internal pressure; A_i is the internal cross-sectional area of the riser; p_e is the external pressure around the riser; A_e is the cross-sectional area of the riser; $f_{(z)}$ is the lateral load per unit length; w_t, w_i and w_e are the weights per unit length of the riser, the internal fluid, and the displaced fluid, respectively; x is the in-line axis; and z is the vertical axis.

3.4 Numerical modeling of the STLP system

Details about the physical model of the STLP have already been introduced. However, from the riser's design point of view, it is important to further point out that the final top tension is un-adjustable as the position is fixed relative to the wellhead of the SSP. Besides, the final top tension will be almost constant since the STLP primarily suffers from the steady current induced load while the influence of direct wave loading is minimized.

Marine dynamics program Orcaflex (Orcina, 2012) is used to model STLP configuration. The SSP is modeled as a 6-degree of freedom lumped buoy, whose geometric and hydrodynamic properties are accurately derived and imported into Orcaflex. All rigid risers and tethers are simulated by a line unit, and a line contact model is used to simulate the interaction between the keel joint and the SSP. The rigid riser including the outer casing and tubing is translated into an "equivalent riser" by using the equivalent method. Then, the finite element model for the equivalent riser is built. Note that the contribution from the production tubing is considered to influence the bending and torsional stiffness simply but the axial stiffness (Bai and Bai, 2005).

A great amount of time was dedicated in the present study to develop a proper way of modeling required constant top tension on the rigid risers. As the risers are tied to the SSP directly without stroke, the conventional tensioning model of Winch provided by the Orcaflex is not suitable. The final solution to this problem is to adjust the risers' length to meet the top tension requirement when the total net buoyancy provided by the SSP is determined. Fig. 6 is an illustration of the STLP global modeling consideration.

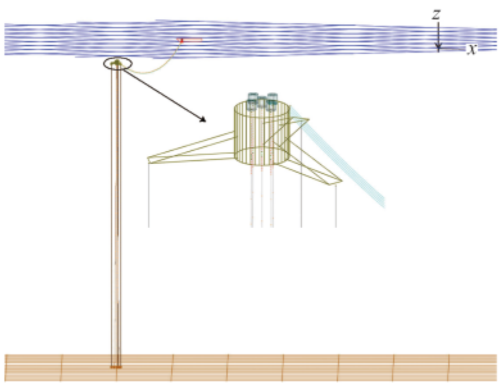

Fig. 6. STLP global finite element model.

4 Analysis and result discussion

Up to now, the STLP system has been still a relatively new subsurface development concept and its details are not disclosed systematically in the existing literature. Thus, it is important to investigate the behavior of the STLP in UDW with respect to its unique features of pre-installation, which is of great importance for the subsequent operations of the SWC equipment and flexible jumpers. In this study, the governing environment condition is the ocean current. Wave effects on the STLP can be found in the academic paper (Zhen et al., 2014) if the readers are interested in this new technology.

4.1 Mooring analysis

In order to ascertain the effect of the mooring system on the behavior of STLP, sensitivity studies on the following parameters including the top inclined angle (θ), pretension (T), water depth (H) and current velocity (v) are performed for the SSP/tethers system.

(1) Top inclination angle of the tethers with the vertical: 0°–5° for 1° interval; 5°–70° for 5° interval.

(2) Initial pretension: (25%–50%) *M.B.L* at a regular interval of 5% *M.B.L*.

(3) Water depth: 2000 m, 3000 m.

(4) Current velocity: 0.50 m/s, 0.75 m/s, 1.00 m/s, 1.25 m/s, 1.50 m/s.

Here, the dimensionless parameters Δ/H, $T/(\rho H^3)$, $\mu v/(\rho H^2)$ are obtained by using the Buckingham Pi method, where Δ is the horizontal offset of the SSP, ρ is the specific weight of fluid, and μ is the viscosity of fluid.

The effects of the top inclined angle on the trim and offset of the SSP are illustrated in Fig. 7 and Fig. 8, respectively. It can be seen from Fig. 7 that the trim angle of the SSP firstly increases dramatically and then decreases, so it has a marked peak value when the inclined angle reaches around 12°. The tilting of the SSP results from the asymmetrical hydrodynamic loads on the tethers, where the current tends to reduce the top tension of the downstream tethers and thus allows the downstream cantilevering to lift. In contrast, the upstream cantilevering is pulled down. In addition, the decrease of the trim angle is attributed to the increased horizontal stiffness provided by the inclined tethers. So does the decrease of the SSP offset in Fig. 8. Nonetheless, the inclined tethers will have a large coverage against field layout. From Figs. 7 and 8, it can be concluded that in order to meet the requirements of the SSP stability as well as optimize the seabed layout, the STLP mooring pattern consisting of vertically loaded tethers is eventually selected.

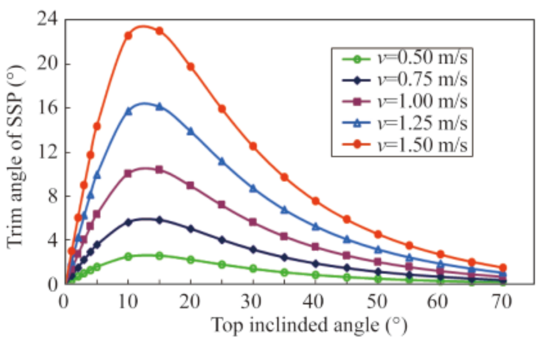

Fig. 7. Effect of the inclined angle on the trim of the SSP.

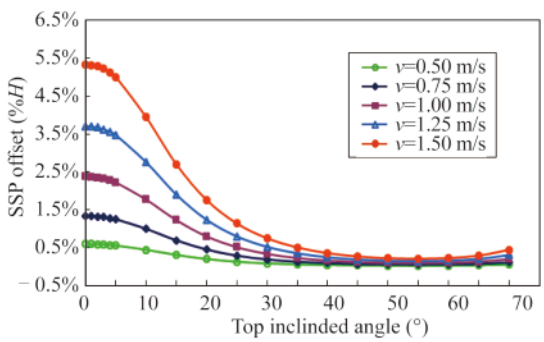

Fig. 8. Effect of the inclined angle on the SSP offset.

Dimensionless design charts for two different water depth subjected to various pretensions and current velocities are presented in Fig. 9. It can be seen that the increased pretension will reduce the SSP excursion while an increase in current velocity and water depth has the opposite effect. It should be noted that, in a certain range, the SSP excursion is comparatively less affected by the increased pretension when the current velocity is small. Thus, the tethers can be designed statically with a higher safety factor when the STLP works in the benign sea state.

4.2 Dynamic behavior of the rigid riser

Maximum envelop for the riser displacements are presented in this section. Influences of the parameters, such as SSP depth, hydrodynamic coefficients, the ocean current velocity, *TTF*, elasticity, and the internal fluid are investigated. Here, the typical environment condition of 100-year return period typhoon current profile in the South China Sea, as shown in Fig. 10, is selected to investigate the dynamic behavior of the rigid riser.

The influence of hydrodynamic coefficient variations for the riser and SSP on the riser motion is investigated, as shown in Figs. 11–13. It can be seen that the riser in-line displacement is increased with the increase of the drag coefficients of both the riser and SSP, while the variation of the added mass coefficients has little effect due to the dynamic nature of the added mass. For the transverse displacement, it can be observed from Figs. 12 and 13 that smaller motion is observed for the riser along its length when the hydrodynamic coefficient is increased. Especially, the transverse riser motion is decreased in Fig. 12 due to the increase of the drag which acts to dampen the motions in this direction.

Fig. 14 shows the envelop of the maximum displacement when the ocean current velocity varies. As has been expected, larger in-line displacements are observed due to the drag when the current intensity increases. On the other hand, the transverse riser motion is in general decreased due to the viscous drag damping.

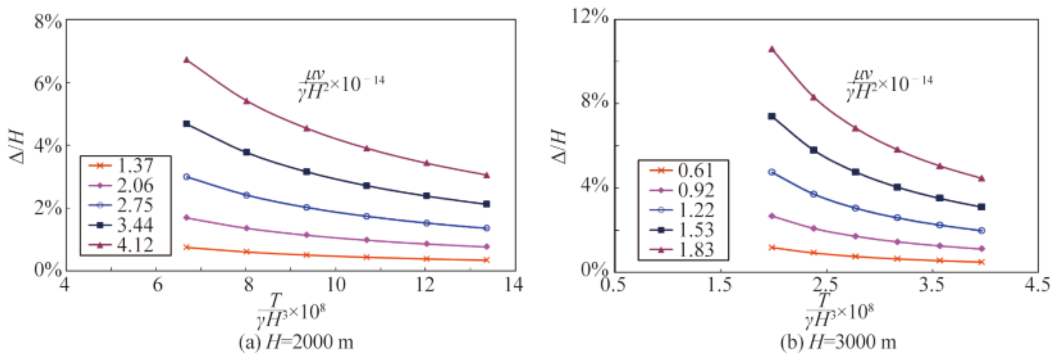

Fig. 9. Dimensionless design charts.

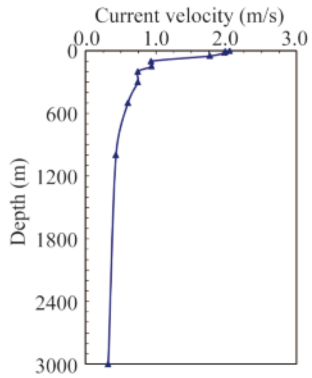

Fig. 10. Current profile.

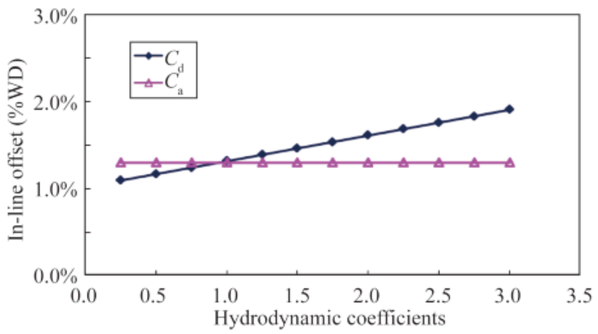

Fig. 11. Hydrodynamic coefficient influence of the SSP on the riser motion at the top end.

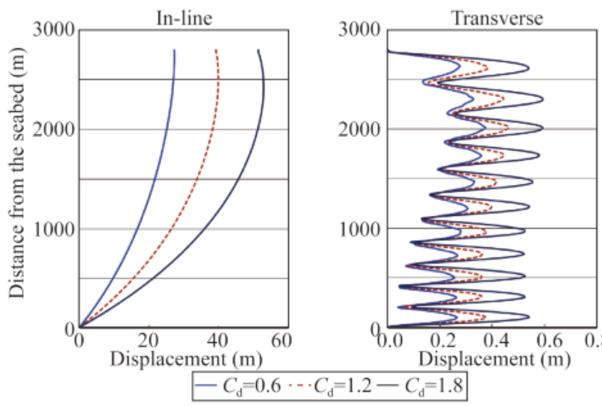

Fig. 12. Maximum amplitudes of the riser displacement for different drag coefficients with the riser.

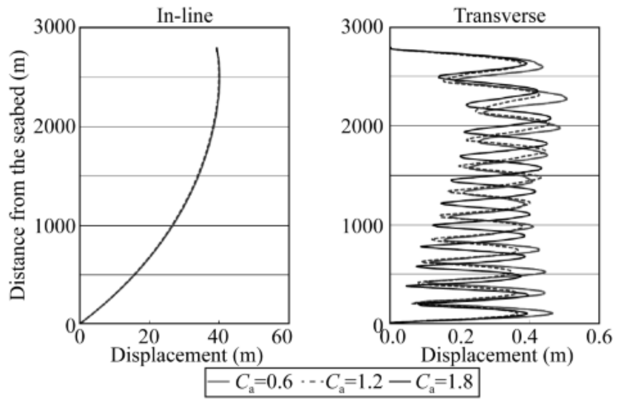

Fig. 13. Maximum amplitudes of the riser displacement for different added mass coefficients with the riser.

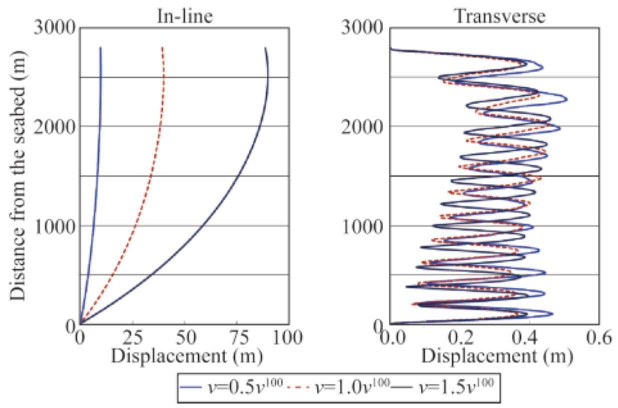

Fig. 14. Maximum amplitudes of the riser displacement for different ocean current velocities.

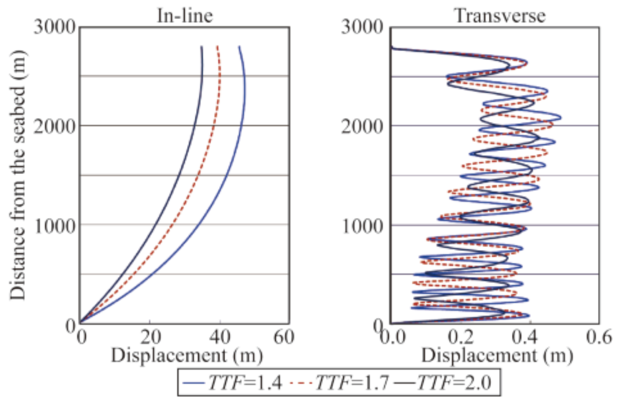

Fig. 15. Maximum amplitudes of the riser displacement for different *TTF*.

It can be observed from Fig. 15 that the riser's top tension has significant influence on the behavior of the riser, and the increase of *TTF* increases the global stiffness of the riser, and consequently smaller displacement is expected for the riser.

The riser motions with different elasticity shown in Fig. 16 are of great concern for the designers due to its relationship with the riser configuration, in which either one or two layers of the casing outside the production tubing are normally used. Nonetheless, it is interesting to see that no significant variations can be noted for the riser displacement. In this case, the dual barrier system has no advantage over the single barrier system. The influence of the riser's elasticity parameter will be further investigated in the next section of global interference analysis.

The effects of the internal fluid on the response of the riser are illustrated in Figs. 17–19. Fig. 17 shows the effect of the presence of petroleum fluid in the production tubing.

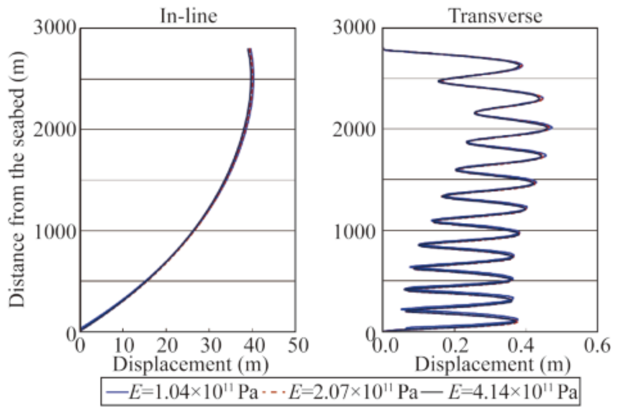

Fig. 16. Maximum amplitudes of the riser displacement for different elasticities (E).

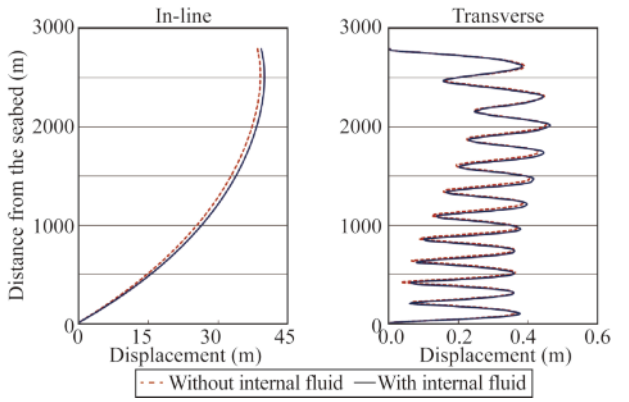

Fig. 17. Maximum amplitudes of the riser displacement with and without internal fluid.

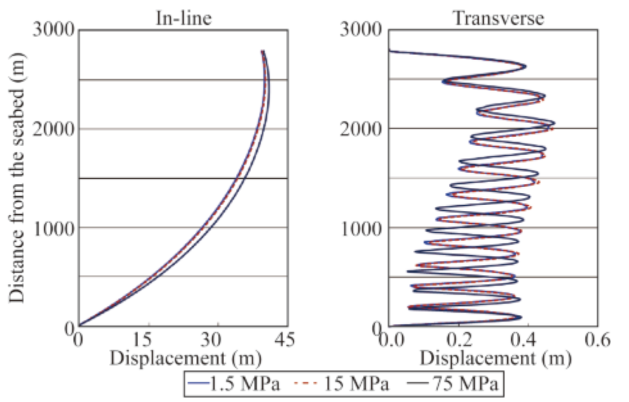

Fig. 18. Maximum amplitudes of the riser displacement for different internal flow pressures.

In this case, the presence of the internal fluid affects the effective tension, and consequently the overall stiffness of the riser. The riser displacement with the internal fluid appears a little bit larger than that without the internal fluid case. Fig. 18 presents results for the cases including internal pressure effects. It can be noted that in the case of higher internal pressure pattern, the riser displacements are little larger

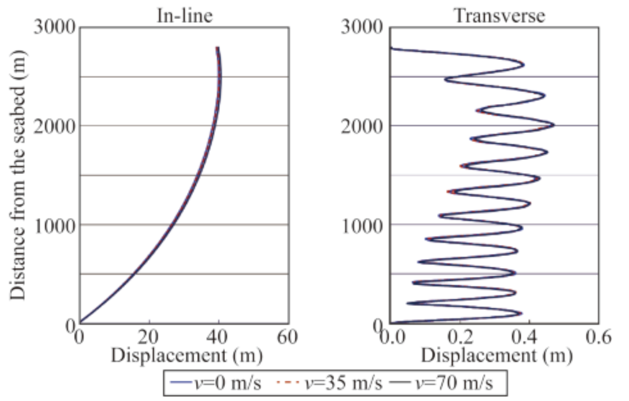

Fig. 19. Maximum amplitudes of the riser displacement for different flow velocities.

than those in other cases. The reason for that is the internal pressure will reduce the riser's effective tension. The effect of different flow rates on the response of the riser is shown in Fig. 19. One can observe that there is only a small difference on the riser response with the variation of the flow rates in the present study. As a conclusion, though the effects of the internal flowing fluid on the riser's dynamic response are not that obvious, special attention should be paid on the internal flowing fluid, such as the presence of petroleum fluid, the internal pressure, and the internal flow rate, which can alternate the riser's nature frequency and when it is near the vortex shedding frequency, the response of the VIV will increase and the fatigue life of the riser will decrease largely.

4.3 Global interference analysis

The interference assessment is carried out between the risers in slots S-01 and S-05, as illustrated in the field layout of Fig. 3, and the riser in slot S-05 is considered as the downstream riser. The influence of the main parameters, such as *TTF*, riser spacing, elasticity, and ocean current velocity is studied in this study. Here, the environment condition of 100-year return period typhoon current profile is selected as well.

From Fig. 20 to Fig. 24, the results indicate that the min-

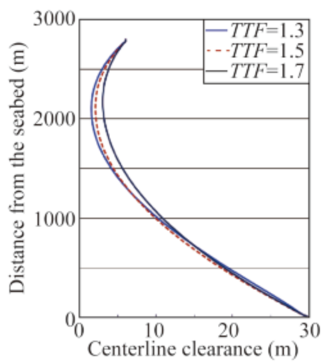

Fig. 20. Centerline clearance as a function of the depth for different *TTF*.

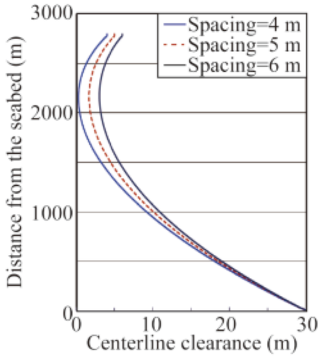

Fig. 21. Centerline clearance as a function of the depth for different riser spacing at the SSP deck.

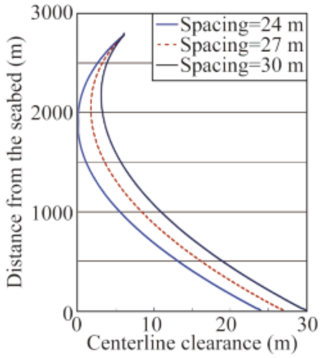

Fig. 22. Centerline clearance as a function of the depth for different riser spacing at the seabed.

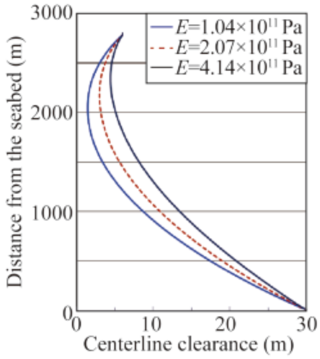

Fig. 23. Centerline clearance as a function of the depth for different elasticities (E).

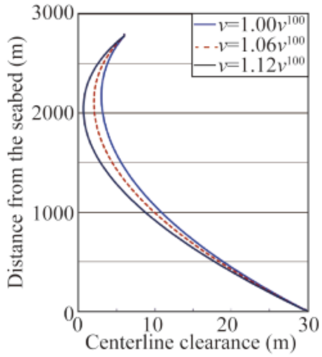

Fig. 24. Centerline clearance as a function of the depth for different current velocities.

imum separation distance between the risers in slots S-01 and S-05 in the present STLP design meets the requirement of the allowable separation distance as stated by DNV-RP-F203. Besides, it can be observed that the minimum clearance occurs in the upper middle section of the riser. From Fig. 20 to Fig. 23, it is shown that the minimum clearance increases with the increase of *TTF*, riser spacing and elasticity, respectively. Nevertheless, it can be found that the increase of the riser spacing and elasticity is a much more efficient way than the control of the top tension to avoid clashing with respect to the STLP concept. In Fig. 21, it can be seen that the well spacing at the SSP deck is much smaller and is mainly driven by the dimensions of the SWC equipment and rigid jumper arrangement. It can be concluded from Fig. 22 that the spacing between adjacent wells at the seabed is about one percent of the water depth to avoid interference. Advantageously, compared with the traditional dry tree platforms, ensuring no interference between adjacent risers by increasing the riser spacing will not result in the significant cost penalties due to the influence on the global FPU parameters as the STLP design and operation principles are relatively independent of the FPU. Besides, it can be seen from Fig. 23 that the risers with lower elasticity are more susceptible to riser interference, thus from this aspect great care needs to be paid on the determination for the riser configuration, whether single casing or dual casings as described in the previous section will be finally selected in the design of the STLP. It should be noted that the reason why the control of the top tension in reducing the risk of clashing is not significant is that the top tension varies with the SSP offset in the application of the "fixed" tensioner. Fig. 24 illustrates that the minimum centerline clearance is susceptible to the variation with the current velocities. Therefore, the extreme design environment must be taken into account in the riser interference analysis. Moreover, with the unique feature of the STLP, it is interesting to see that the top tension of the upstream risers will be further increased while the downstream risers are on the contrary due to the SSP offset, which is conducive to reducing the potential risk of riser clashing.

5 Conclusions

This paper focuses on the parametric study on the behavior of the STLP, which is aimed to act as the aided subsurface petroleum production and exporting system together with any FPU in UDW. Extensive parametric studies and comparisons are carried out. The main conclusions are as follows:

(1) The mooring configuration with vertical loaded tethers should be chosen in order to meet the requirements of

the SSP's stability as well as optimize the seabed layout with respect to the unique design features of the STLP.

(2) The determination of the SSP submergence needs a special consideration, where as the wave effects should be minimized with regard to its influence on the heave motions of rigid risers.

(3) Parametric evaluations for the riser displacements emphasize that the most important parameters are the drag coefficient, *TTF*, and ocean current velocity. These results are of key importance to guide situations to control the riser's response.

(4) The assessment of the riser interference indicates that the increase of the riser spacing is a much more efficient way than the control of the top tension to avoid interference. The spacing of at least one percent of the water depth between adjacent wells at the seabed is recommended to avoid interference. Besides, with the unique feature of the STLP, it is conducive to reducing the potential risk of riser clashing with respect to the top tension variation of the upstream and downstream risers due to the SSP offset.

(5) Great concern needs to be taken to the riser configuration, whether single casing or dual casings will be used, because the variation on the elasticity has a significant influence on the riser interference though little effects exist on the riser motions.

In summary, the parametric study on the behavior of the STLP confirms the technical feasibility and superiority of this system as the alternative for well and riser solution in UDW. The STLP behaves almost quasi-statically and can eliminate nearly all wave induced challenges for the conventional offshore production systems by using proven components and technologies. The above research results and conclusions can be used as guidelines for the design and operation of the future SWC facilities. In addition, owing to its innovative hierarchical design, the STLP is adaptable to severe sea-surface environmental elements. Nonetheless, the internal waves have become the critical environmental factor for the STLP's lifecycle safety. Further studies on the dynamic characteristics of the STLP in internal waves are on progress.

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