# Transport Studies of the Innovative Vertical Buoy Supported Risers System

Magnus C. de V. Prata [1] , Christie de V. P. Machado [1] , Breno P. Jacob [1] , Fabrício N. Corrêa [1]

[1]*Civil Engineering Program – PEC/COPPE, Federal University of Rio de Janeiro – UFRJ*
*Avenida Pedro Calmon, s/n, Cidade Universitária, Ilha do Fundão, 21941-596, Rio de Janeiro/RJ, Brazil*
*magnus@coc.ufrj.br, christie@coc.ufrj.br, breno@lamcso.coppe.ufrj.br, fabricio@lamcso.coppe.ufrj.br*

**Abstract.** The current expansion of offshore oil and gas exploration in increasingly deeper water depths leads to an option of utilization of hybrid riser systems. Among the offered types of hybrid riser systems, one of them employs a Buoy Supported Risers (BSR) as an intermediate element between the jumpers and the SCRs. Although the hybrid riser system utilizing BSR provides a very effective ultra-deep water riser system, the use of BSR entails high costs, complexity and considerable risk during the transportation and buoy installation steps. In this way, new alternatives regarding the use of hybrid risers are welcome. In this context, this work presents the innovative proposal of a Vertical Buoy Supported Risers (VBSR) that may offer greater viability when compared to the traditional horizontal concepts, resulting in benefits for hybrid riser systems. The benefits of vertical configuration of the BSR, in relation to the conventional horizontal one, are more focused on transport and installation risks reduction, although also presents vantages in operational phase. In this work, the presented study is focused on the transport stage of the VBSR. Therefore, an evaluation of the VBSR's static and dynamic responses during transportation in intact and damage scenario are presented here.

**Keywords:** hybrid risers, Vertical Buoy Supported Risers, static and dynamic simulations.

## 1 Introduction

The great advance in oil exploration into increasingly deeper waters in recent decades around the world is undeniable. In Brazil, the milestone in the advancement of the oil industry into waters deeper than 2000m was the exploration of the pre-salt. One of the challenges faced in places with high water depths is the choice of the type of riser used to connect the extensive section between the well and the floating platform. Therefore, the riser must be able to resist various efforts ranging from static loads, involving their own total weight, pressure from water column and current profile, to dynamic loads resulting from the movement of the floating unit and the action of sea waves, as described by Malta [1].

Seeking to achieve better riser performance in the deep and ultra-deep water environment, the concept of the hybrid riser system emerges. According to Araújo *et al.* [2], there are some models of hybrid systems developed, one of which uses a Buoy Supported Risers (BSR) as an intermediate element between flexible risers (jumpers) and rigid catenary risers (Steel Catenary Risers – SCRs). Although the system using BSR manages to combine the advantages of both types of risers, providing a very effective system compatible with ultra-deep waters, it presents high cost, high complexity and considerable risk in the transport and installation stages. Furthermore, the operational window of these two phases is small. Therefore, one can be seen that the hybrid riser conceptions are still in development, being an encouraging context for new alternatives to be created and studied, and it is in this context that the present work is introduced.

Seeking for a more stable behavior along the transport, installation and operation, the innovative proposal of the Vertical Buoy Supported Risers (VBSR) emerges. This new vertical configuration of the BSR may have greater viability when compared to the traditional horizontal configuration, which would represent gains for hybrid riser systems and, consequently, for oil and gas exploration activity.

The objective of the present work is to evaluate the behavior of VBSR in the transport stage, carrying out studies on its static and dynamic response during this stage. Comparisons between its behavior and that of the traditional horizontal BSR configuration are also presented.

# 2 Hybrid risers

The hybrid riser system consists of a combination of flexible risers and rigid risers, connected by a floating system in order to enhance the strengths of each type of riser. Three hybrid systems can be presented in different forms, such as: Hybrid Riser Tower (HRT), Single Hybrid Riser (SHR) and the hybrid system using BSR. The most recent use of a hybrid riser applied by Petrobras was the BSR concept, in the Sapinhoá and Lula field, located in the pre-salt Santos Basin.

## 2.1 Buoy Supported Risers (BSR)

According to Almeida [3], in the BSR system flexible risers (jumpers) are used in the section that connects the platform to the buoy, making this type of riser absorb the first-order movements of the vessel and the effects caused by wave action, which is notable in the region closest to the surface. As the flexible riser has a greater fatigue life than the rigid riser, it ends up becoming more suitable for this section. For the section from the buoy to the well, rigid risers are used, as they allow great depths to be reached with different diameters, in addition they are significantly cheaper than the flexible riser. Additionally, the installation procedure must be taken into consideration to ensure which type is the cheapest between flexible and rigid risers. Thus, it is clear that the hybrid riser concept with BSR was developed to mix flexible and steel catenary risers to bring the best advantages of each type to reach ultra-deep waters.

In the connection region between the flexible and rigid risers, the buoy performs the important function of promoting a decoupled system, so that only a small part or none of vessel's movements are transmitted to the risers in the lower section. Minimizing the movements of rigid risers results in reducing efforts in the touch down zone (TDZ), which is one of the most critical regions regarding riser fatigue, as exposed by Almeida [3].

Although the BSR is not directly affected by wave action due to the depth at which it is installed, dynamic loads reach it through the propagation of the platform's heave movements through the jumpers. This in turn causes a rotation of the BSR around the SCRs' pontoon, which leads to amplifications of the tensions of the tendons connected to the jumpers' pontoon. Although the movement is not very intense, when applied in a period close to the natural frequency of the BSR system, a resonant BSR response can occur, as said by Cruz *et al.* [4]. Figure 1 shows a schematic of how the movement of the floating platform causes dynamic effects to the BSR system.

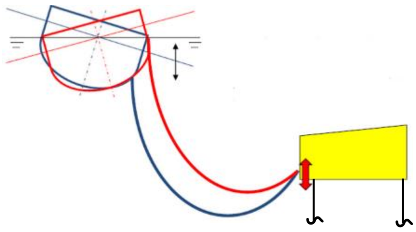

Figure 1. Dynamic loads applied to the BSR. Adapted from Cruz *et al.* [4]

Hiller *et al.* [5] makes it clear that the BSR used in the Petrobras project was approximately 40m x 52m, being installed at a depth of 250m and fixed by 8 tendons, two at each corner of the buoy. Furthermore, the BSR is made up of 48 compartments that control the ballast and buoyancy necessary in the transportation and installation process. The balance between the pressurized and ballasted compartments is necessary to balance the momentum of the loads to ensure adequate buoyancy conditions. Figure 2 shows the BSR with its compartments, and the number and location of compartments to be ballasted or pressurized varies depending on the transport/installation stage.

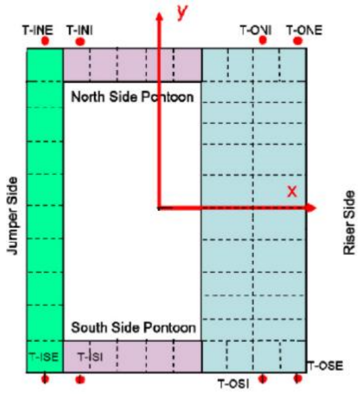


Figure 2. BSR compartments. From Cruz *et al.* [4]

The dimensions of the BSR pontoons were designed to neutralize the loads applied to them, preventing large bending moments from being transferred through the structure. For this reason, the pontoon related to the SCRs is larger than the pontoon related to the jumpers, as it needs to be able to support the large load of the rigid risers that rest on it.

### 2.2 BSR transport

To carry out the transport and installation of the BSR, some specific environmental conditions are necessary. Through numerical simulations, it was found that for $Hs > 1$m at depths of up to 30m, the BSR presented large vertical dynamic movements. And for depths greater than 30m, it is necessary that $Hs \leq 2.5$m and the current $\leq 0.4$m/s so that the buoy does not present significant movements, as described by Girón [6].

BSR transportation is carried out with the participation of two AHT (Anchor Handling Tug) vessels. For this activity, each of these vessels has two bundle-chains, each of which is connected to a different winch, thus totaling two winches on each tugboat. Furthermore, the weights of the BSR compartments are adjusted so that it is partially emerged, as explained by Cruz *et al.* [4] and Girón [6]. Figure 3 shows the transport of a BSR, illustrating its partially emerged position.


Figure 3. BSR transport position diagram. Adapted from Cruz *et al.* [4]

## 3 New hybrid riser design: Vertical Buoy Supported Risers (VBSR)

The innovative Vertical Buoy Supported Risers (VBSR) concept was developed to improve the stability and safety of the float compared to the conventional horizontal position. Furthermore, this new design is also expected to have a larger transport and installation operational window. The study of this new design was dedicated in this work to the transport stage of the VBSR using a buoy with 50m high and 52m long. It is worth noting that the present study does not aim to evaluate the ideal shape of the buoy, therefore, the VBSR was represented in such a way that, in terms of volume, it was close to that of the BSR presented before.

In this work, the transport stage is evaluated, and unlike the BSR transport, in which the buoy is semi-submerged, during the VBSR transport the buoy is completely submerged. A transport depth of 90m was adopted for the base of the buoy, so that there is still a free water column of 40m above the top of the buoy. Just like the BSR, the vertical displacement of the VBSR cannot exceed 50m without proper pressure adjustment to avoid the structural collapse of the buoy. For this reason, this transport depth was chosen, as this minimizes risks, since even if the buoy rises to the surface during transport, it will move vertically a maximum of 40m, being a value smaller than that responsible for cause the buoy to collapse.

The creation of transport models and their subsequent analyzes were carried out using the SITUA-Prosim program, developed by the Laboratory of Computational Methods and Offshore Systems - LAMCSO. All of these models share the same base consisting of two tugboats equipped with two winches each, with a transport line connected to each winch. In this way, the buoy is transported by four lines, two on each side of its base. Furthermore, near the lower sides of the buoy, four tendons were connected (two on each side). Figure 4 presents the elements present in the VBSR transport model and the axes associated with the buoy.


Figure 4. VBSR transport model highlighting the axes associated with the buoy

Each of the transport lines is composed of an initial section connected to a 50m long steel cable buoy, followed by an intermediate section of chains with 86m, and finally, another section of 181m long steel cable connecting the line to the tugboat winch. The vertical weight of the transport lines, working together with the buoy's tendons and a specific ballast configuration of the vertical buoy, are all responsible for keeping the buoy submerged at the transport depth of 90m.

The transport of the VBSR can be carried out entirely without the presence of tendons or with them present, provided that there is sufficient depth for the length of the tendons. In this study, only the transport situation in which the tendons are present was considered, discarding the initial moment in which the tendons have not yet been connected. It was decided to analyze only the part of the transport in which the tendons are connected, since this is a more critical situation, as it involves the possibility of tendons failure, in a rupture configuration in which one or more tendons may come loose from their connection points. Each of the four tendons has a mass of 106.2t and is made up of an initial section, close to the buoy, of polyester 54m long, followed by a long section of steel cable measuring 1830m, and ending with a 1m connection section.

## 4 Cases analyzed of VBSR transport

To study the transport of the VBSR, it was considered that it occurs towards the east and five transport speeds were evaluated, which would be the speeds used by the two tugboats: 0m/s; 0.5m/s; 1m/s; 1.5m/s and 2m/s. Furthermore, a group of annual environmental loadings with wave and current data was defined. Four wave loads with different wave heights ($Hs$) and natural periods ($Tp$) were chosen, all of them with a direction coming from the NE (45°). Table 1 presents data for each of the wave loadings considered for the analyzes.

Table 1. Annual wave loadings considered

| | Sea 1 | Sea 2 | Sea 3 | Sea 4 |
|---|---|---|---|---|
| $Hs$ | 2m | 3m | 5.29m | 6.86m |
| $Tp$ | 8s | 8s | 13s | 12s |
| Direction ("coming from") | NE (45°) | NE (45°) | NE (45°) | NE (45°) |

Regarding current loading, three current directions were analyzed, which are: west (W), east (E) and north (N). The current in the west direction is contrary to the movement of the buoy and tugboats, while in the east it acts in the same direction as the transport. The north current affects the system perpendicularly. For all currents assumed, a current profile with constant direction was considered. Furthermore, the profile with a speed of 1.14m/s at surface and 0.72m/s at a depth of 100m was chosen. Figure 5 illustrates the model in an orthographic top view, highlighting the direction of transport with arrows.

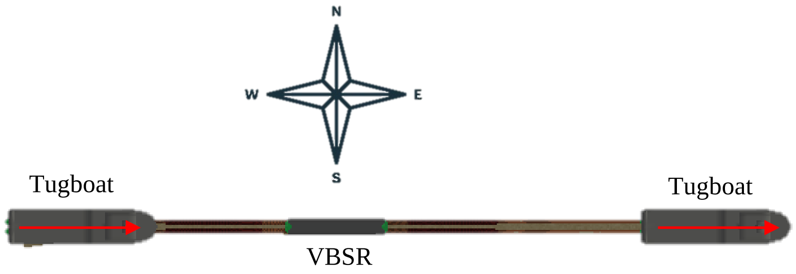


Figure 5. Transport model with orthographic view, indicating the direction of transport with red arrows

In this way, a group of models resulting from the combination of varied wave loads, current and tugboat speeds were analyzed.

### 4.1 Results of VBSR transport simulations

Through the analyzes carried out, three situations that can occur with the buoy were observed, each of which is associated with a color, which are:

- VBSR moves excessively, so that it is very close to or under the rear tugboat (red);
- Top of the buoy reaches the surface, but maintains a safe distance from the tugboats (yellow);
- None of the previous options, i.e., VBSR has good behavior (green).

The first item listed, associated with red, represents problematic and limiting cases for the transport phase. The second item, identified by yellow, is not a limitation for transport, but requires attention and it is preferable to avoid the buoy reaching the surface. It is worth noting that this situation is not limiting due to the transport depth, as if the buoy were transported at a depth of 100m or more, the buoy would fail upon reaching the surface. And finally, the last item, identified by green, is the ideal situation for transportation.

Table 2, Tab. 3 and Tab. 4 present the results of the analyzes carried out, with Tab. 2 referring to the models using west current, Tab. 3 east current and Tab. 4 north current. The three tables present the values of the maximum vertical displacement of the float measured in each of the models analyzed. Each of these values has one of the three colors presented (red, yellow or green), explaining the behavior of the buoy in its respective analysis.

Table 2. Maximum vertical displacements of the VBSR - west current

| Tugboat speed (m/s) | Sea 1 | Sea 2 | Sea 3 | Sea 4 |
|---|---|---|---|---|
| 2.0 | +24.45m | +32.81m | +42.95m | +43.93m |
| 1.5 | +14.82m | +17.92m | +23.45m | +43.91m |
| 1.0 | +7.91m | +9.79m | +14.93m | +24.86m |
| 0.5 | +4.08m | +5.76m | +9.55m | +17.37m |
| 0.0 | +2.36m | +4.45m | +8.13m | +14.31m |

Table 3. Maximum vertical displacements of the VBSR - east current

| Tugboat speed (m/s) | Sea 1 | Sea 4 |
|---|---|---|
| 2.0 | +3.27m | +15.65m |
| 1.5 | +2.27m | +13.86m |
| 1.0 | +2.01m | +13.11m |
| 0.5 | +2.30m | +13.27m |
| 0.0 | +2.83m | +14.11m |

Table 4. Maximum vertical displacements of the VBSR - north current

| Tugboat speed (m/s) | Sea 1 | Sea 3 | Sea 4 |
|---|---|---|---|
| 2.0 | +20.8m | +35.29m | +44.33m |
| 1.5 | +17.92m | +28.28m | +43.21m |
| 1.0 | +16.36m | +26.11m | +42.30m |
| 0.5 | +15.80m | +25.69m | +42.40m |
| 0.0 | +15.64m | +24.97m | +42.89m |

The main objective of considering different seas was to be able to evaluate the behavior of the buoy for high (sea 4) and lower (sea 1) wave heights. More wave heights were analyzed for the situation where the west current is applied as it showed to be more critical. It is important to highlight that to consider the transport speed, the vector sum of the current speed and the transport speed was performed, and the resultant was applied in the numerical model to the current profile. In this way, through the results obtained, it is possible to know the behavior of the VBSR for a series of other combinations of current and transport speeds.

### 4.2 Failure case: transport line and tendon rupture

Two forms of system failure were studied individually, the rupture of one of the transport lines and the rupture of a tendon. In the event of a line break, the line that connects the buoy to the tugboat behind was chosen. For this case of failure, two different situations were analyzed, the rupture occurring in the tugboat-line connection and in the line-buoy connection.

For the line rupture failure analysis, the model with west current, transport speed of 0.5m/s and sea 4 was chosen. This model was chosen because it is associated with the current that proved to be more sensitive, in addition to this model applying the highest wave height (sea 4) at the same time as this is the case where, with the system intact, the buoy behaves well. Table 5 presents the maximum vertical displacements obtained in the two transport line rupture analyzes carried out, with the meaning of the colors already explained previously.

Table 5. Maximum vertical displacements of the VBSR - west current and transport speed of 0.5m/s

| Line rupture in the tugboat connection | Line rupture in the buoy connection |
|---|---|
| -27.97m | +43.23m |

As expected, the buoy sinks when the line is broken in connection with the tugboat, as the entire weight of the line is now supported by the buoy. The opposite occurs when the rupture occurs in the connection with the buoy, as it is the tugboat that now supports the entire line, resulting in a weight relief for the buoy.

The other failure analyzed was the rupture of one of the tendons, and a static analysis was carried out for this failure, without any environmental loading. It was found that the buoy rises 34m, arriving very close to the surface. Another characteristic is that its balance is reached with the VBSR rotated approximately 33° around its x-axis.

## 5 Conclusions

The objective of the present work was to evaluate the behavior of a new concept of hybrid riser using a vertical BSR (VBSR) in the transport stage, carrying out studies on its static and dynamic response during this stage. Observing the results presented, the current profile that acts in the opposite direction to transport, which in the case of this study was the west current, showed to be the most limiting in terms of transport speed. Therefore, considering a current speed of 1.14m/s, the transport must be carried out at a speed of 0.5m/s because the vertical buoy is already moving excessively backwards with a tugboat speed of 1m/s. The increase in transport speed could only occur by decreasing the speed of the current. Despite this speed limitation, the buoy maintained good dynamic behavior, considering a transport speed of 0.5m/s, even under waves of 6.86m high.

The current in the direction of transport (eastern current) proved to be an excellent scenario for transporting the buoy, since even under the effect of 6.86m waves the buoy showed good behavior for all transport speeds.

In the case of the current that acts perpendicular to the system, the buoy showed unfavorable behavior for wave heights of 6.86m, as the top of the buoy reached the surface at all transport speeds studied. However, this no longer occurs at wave heights of 5.29m.

Considering the results of all analyzed currents, transport can be carried out adequately in a scenario with $Hs \leq 5.29$m and transport speed $\leq 0.5$m/s, considering a current $\leq 1.14$m/s speed. If the current has a slower speed, the transport speed could increase. Thus, knowing that the operational window of BSR is limited to $Hs \leq 2.5$m and current $\leq 0.4$m/s, it is concluded that the operational window of VBSR was considerably larger, showing advantages in relation to BSR.

Furthermore, transporting the VBSR with the buoy completely submerged proved to be a good choice, as it gave the buoy stability. Thus, VBSR proved to be a promising innovative proposal, requiring further studies regarding the installation and operation phases.

**Acknowledgements.** The first author thanks the Brazilian Program PRH – 09 from COPPE/UFRJ and the agencies ANP and Petrobras.

**Authorship statement.** The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

## References

[1] E. R. Malta. Projeto de um Riser Flexível para Águas Ultraprofundas. Undergraduate thesis, University of Sao Paulo - USP, Sao Paulo, SP, Brazil, 2010.

[2] J. B. Araújo *et al.*, "Simulação Numérica e Ensaio Experimental da Bóia de Sub-Superfície de Suporte de Risers - BSSR", *Rio Oil & Gas Expo and Conference 2004*, Rio de Janeiro, RJ, Brazil, 2004.

[3] J. C. L. Almeida. Instalação de Sistema com Bóia de Subsuperfície para Suporte de *Steel Catenary Risers* de Produção em Águas Ultra-Profundas. M.Sc. thesis, COPPE/UFRJ, Rio de Janeiro, RJ, Brazil, 2000.

[4] I. Cruz *et al.*, "The Buoy Supporting Risers (BSR) System: Engineering a Solution for Ultra-Deep Water Subsea Developments in Harsh Environments", *Offshore Technology Conference*, Houston, TX, USA, 2015.

[5] D. Hiller *et al.*, "Developing an Innovative Deepwater Riser System: From Concept to the Full Production of Buoy Supporting Risers (BSR)", *Offshore Technology Conference*, Houston, TX, USA, 2015.

[6] A. R. C. Girón, "Boyas de Soporte de Risers "Análisis de Instalación" ", *Congreso Ingeniator*, 2022.