CONCEPT APPLICATION FOR PIPELINES USING A SUBMERGED FLOATING TUNNEL FOR USE IN THE OIL AND GAS INDUSTRY

by Ery Budiman

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ABSTRACT

This paper describes the effort to develop a pipeline concept as a substitute for conventional pipelines that lie on the seabed. A submarine pipeline in a submerged floating tunnel (SFT) is presented as a potential way to avoid pipeline-related environmental concerns. The key task in developing this submarine pipeline concept is to integrate solutions to the environmental challenges associated with submarine pipelines into the SFT structure.

From a technical standpoint, one of the most important design tasks is to calculate the SFT's buoyancy weight ratio (BWR) value, thereby determining the tunnel's stability. The greatest threat to stability is the phenomenon of tether slack, which occurs at a specific BWR value. The pipeline's weight affects its BWR value, so the weight must be restricted to ensure that tether slack does not occur. In the present study, the proposed SFT's BWR value was simulated by testing a laboratory model in various ballasts. Significant waves and individual waves in a hundred-year return period were investigated based on data related to Java Sea waves at the Indonesian Hydrodynamic Laboratory (IHL).

This study tested the SFT laboratory model against regular waves to find the BWR value at which tether slack might occur. The obtained BWR value was used to determine the requirement for total pipeline weight. Using a 1:100 scale of the real environmental conditions, the laboratory results revealed that slack occurs in a significant wave when the BWR value is 1.2, making the maximum pipeline weight to be placed in the SFT 534 tons. For the individual wave, slack occurs when the BWR value is 1.4, making the maximum pipeline weight to be placed in the SFT 267.214 tons.

Keywords: Advantage of pipeline placement; Buoyancy weight ratio (BWR); Snap loading; Stability; Submarine pipeline

1. INTRODUCTION

A pipeline set in a submerged floating tunnel (SFT) structure is an alternative solution meant to enhance pipeline safety and limit the possibility of environmental damage caused by conventional oil pipelines (Budiman et al., 2016a). The main challenge in designing such a system is the interaction between pipeline and SFT structure, as the weight of the pipeline can influence the SFT's buoyancy weight ratio (BWR). BWR is the ratio of tunnel buoyancy to overall tunnel weight (including the weight of the tunnel structure, the pipeline and its

infrastructure, and cable systems). SFT stability depends on this BWR value (Long et al., 2008; Wahyuni et al., 2012), and the most common threat to this stability is tether slack. Some experiments and numerical efforts had been carried out related to slack phenomena of tether (Huang et al.,1993; Patel et al, 1995; Vassalos et al.,1996; Hennessey et al.,2005). Slack in a cable is a condition in which the tension force of the cable falls to zero, then returns to a taut condition. This produces an impact force known as snap force. It is important issue because it could be one of the most critical conditions and could lead to structural failure like sudden breakage of tether and fracture in the connector plate. The buoyancy of the tunnel must be more than the total weight of the SFT to keep the tunnel in a floating condition and the tether functioning properly. BWR affects the tension force of the cable, thereby influencing the likelihood of slack and snap force occurrence (Lu et al., 2010). Snap force can reach nine times the cable tension force in the slightest slack conditions, depending on the fundamental structural parameters of the SFT and wave parameters (Goeller, 1971). Thus, it is of utmost importance to use laboratory testing to obtain an accurate reading of the BWR value at which tether slack begins to occur and determine the magnitude of the snap force that follows.

This paper examines a proposed submarine pipeline section to extend from an inlet point (likely an onshore compressor terminal) to an outlet point (typically an onshore receiver terminal) in accordance with Det Norske Veritas rule (DNV, 2000). The proposed SFT structure offers an improved alternative solution for transporting oil and gas across seas and straits, the typical function of submarine pipelines (Yong B et al., 2005 ; Guo B et al., 2005 ; Lee P.E.J, 2009), while protecting the pipeline so that the process of transport is safer, more efficient, effective, environmentally friendly, and easily monitored (see Figure 1).
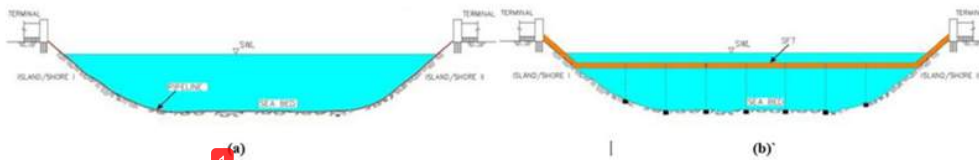

Figure 1 (a) Conventional pipeline case-1; (b) proposed pipeline using SFT case-1

2. EXPERIMENTAL

2.1. SFT Model

The aim of this experiment was to obtain information about BWR values related to cable slack occurrence. These BWR values were used to determine the maximum pipeline weight to be placed in the SFT. The waterway crossing that connects Panggang Island and Karya Island on the Seribu archipelago of Indonesia was chosen as the case study for the present experiment. The bathymetry of the seabed was simplified so that seabed slope at both ends of the crossing wassimilar. The experimental model consisted of a Polyvinyl Chloride (PVC) cylindrical pipe with a diameter of 2 in and a wall thickness of 0.13 cm within a testing model that simulated real environmental conditions on a 1:100 scale (Budiman et al., 2016b). According to this scale, the total crossing length (L) of 150 cm consisted of a flat 60 cm in the central part of the crossing and a 45-cm incline ateach end. The axis of the central part and the two ends differed in height by 13 cm. The seabed depth was 20 cm, representing the average water depth of the archipelago crossing.

The top side of the tunnel was submerged 5 cm beneath the water's surface.The SFT and the shore were linked via hinge–hinge connection. The model used a dual symmetrical tether

configuration in which the outer and inner tethers were tangent to the SFT's body on the middle side (see Figure 2).
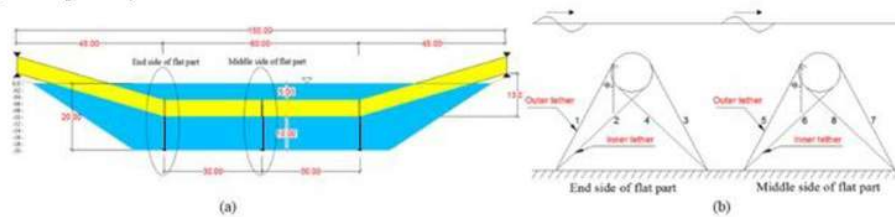

Figure 2 (a) Geometrical tether configuration; (b) numbered SFT tether

2.2. Experimental Setup

2.2.1. Wave generation equipment

A photograph of the flume tank equipped with a wave generator is shown in Figure 3. The flume tank was 20 m long and 2.3 m wide and operated at a nominal depth of 78 mm. The flume had a steel plate beach of 3 m set at a slope of 1:12, covered by a mat of synthetic hair to help absorb and dissipate incident wave energy. The wave generator was driven by a hydraulic system plunyer capable of producing regular or irregular waves within a period of 0.5 to 3 s and wave heights of up to approximately 30 cm.

Figure 3 (a) Flume tank; (b) wave generator

2.2.2. Instrumentation

In testing the SFT model, tension force on the tethers was measured using Polyvinylidene Fluoride (PVDF) transducers, in which sensors were based on piezoelectric material. Eight PVDF-type transducers were installed on the model SFT tethers—four on one end side (representing the symmetry with the other end side) and the others on the middle side of the flat part of the model (see Figure 4).
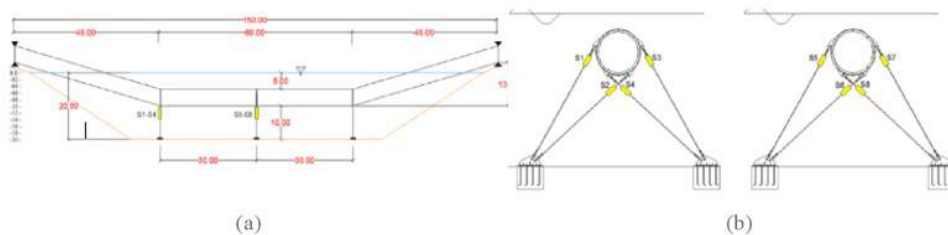

Figure 4 Installation of PVDF sensor: (a) side view; (b) cross-section view

2.3. Testing

A regular wave—a wave with a single height, period, and direction (Bhattacharyya, 1978; Dean & Dalrymple, 2000)—was generated for the SFT experiment. A series of wave heights (1, 3, 5,

7, 9, and 11 cm) and wave periods (4, 6, 8, 10, 12, and 14 s) were applied in the model. The wave parameter data included results from an investigation of Java Sea waves conducted at the Indonesian Hydrodynamic Laboratory-Agency for the Assessment and Application of Technology (IHL-BPPT). According to that investigation, the maximum significant wave height in the hundred-year return period was approximately 5.08 m, the maximum significant wave period 9.08 s, the maximum individual wave height 9.14 m, and the maximum individual wave period 11.81 s (see Table 1). Both wave parameters (significant and individual) were used as reference values for varying the testing parameters within a certain scale.

Table 1 Return period of maximum significant height in the northern gulf of Jakarta, Java Sea (IHL-BPPT,2011)

Return period (years)	Significant wave				Individual wave			
	Hs (m)	Ts (s)	Ls (m)	(H/L)s	Hs (m)	Ts (s)	Ls (m)	(H/L)s
1	2.04	5.81	52.59	0.04	3.67	7.55	89.92	0.04
5	3.92	8.00	97.71	0.04	7.06	10.40	168.84	0.04
10	4.27	8.34	105.36	0.04	7.69	10.84	183.63	0.04
25	4.63	8.68	112.95	0.04	8.33	11.28	198.82	0.04
50	4.87	8.90	117.85	0.04	8.77	11.57	208.93	0.04
100	5.08	9.08	122.03	0.04	9.14	11.81	217.78	0.04

SFT testing can be categorized into two types: static testing and dynamic testing. Static testing in the present experiment aimed to determine the amount of ballast to be used in the BWR, so this type involved only hydrostatic force and structure gravity. The test model was immersed in water to a depth of 5 cm. Each of the two ends was installed with load cells to measure the resultant reaction force. The results of this load cell measurement revealed the difference between the buoyant force and the model's own weight. With this information on how the buoyant force acted on the model at specific depths, a ballast weight was able to be developed for each BWR value.

The dynamic testing involved the structure's own weight, the buoyant force, and the wave force. The wave force applied to the test model was that of a regular wave. This test investigated two parameters: wave parameters and structural parameters. Wave parameter investigations included the wave height and wave period. Structural parameter investigations examined the BWR. The ballast material consisted of a lead sheet installed on the central section of the tunnel body per the designated BWR value. The weight of the ballast material was determined by the following formula:

$$W_B = \frac{B}{BWR} - Ws,$$

$$(1)$$

where W_B is the ballast; B is the buoyant force; BWR is the buoyancy weight ratio, and Ws is the own weight of SFT.

The ballast material was substituted with the corresponding BWR value. The experimental model was assembled as shown in Figure 5. Per the scaling method, experiments using a ship model or other marine structures are always implemented according to Froude's law. The present experiment use the scale of 1:100, as shown in Table 2.
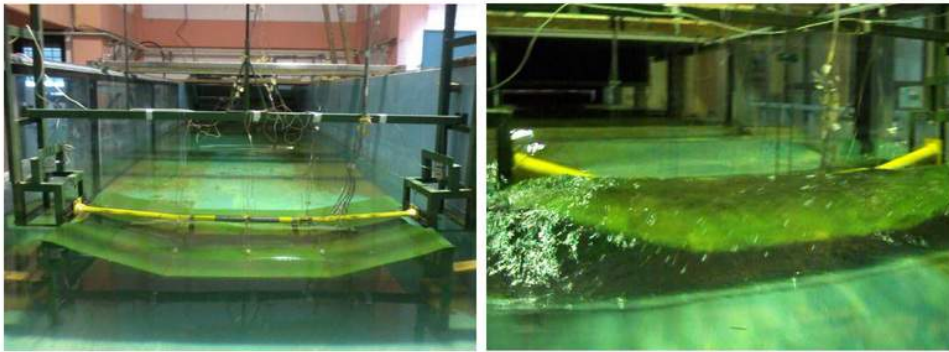
Figure 5 (a) Photograph of test model assembly; (b) tested model

The relationship between the model and the prototype was expressed in several scale models as follows:

Table 2 Scaling of model

Load case no.	Case	Model		Prototype	
		Wave height (cm)	Wave period (s)	Wave height (m)	Wave period (s)
1	Significant wave	5.08	0.908	5.08	9.08
2	Individual wave	9.14	1.180	9.14	11.80

There were three loading history stages for the pipeline, which involved the following:

1. Installation stage: the loading in this stage comprises the pipeline weight and coating weight;
2. Hydrotest stage: the loading at this stage comprises the weights measured at the installation stage plus the hydrotest water weight;
3. Operational pristine stage: the loading at this stage comprises the weights measured at the installation stage plus the hydrocarbon weight;

Each loading history stage was examined to determine the pipeline capacity needed to meet the requirements of the BWR in relation to significant and individual waves.

3. RESULTS

Figures 6 and 7 illustrate the time series of a typical dynamic tether tension response as related to BWR value. The first set of graphs shows the dynamic response to a significant wave; here, the SFT model was subjected to a wave 5.08 cm tall and of a wave period of 0.908 s (sees Figure 6).

The second set of graphs shows the dynamic tether tension response to an individual wave. Here, the SFT model was subjected to a wave height of 9.14 cm and a wave period of 1.18 s, as shown in Figure 7. Both sets were determined based on the results from the IHL-BPPT examination of a hundred-year return period wave.
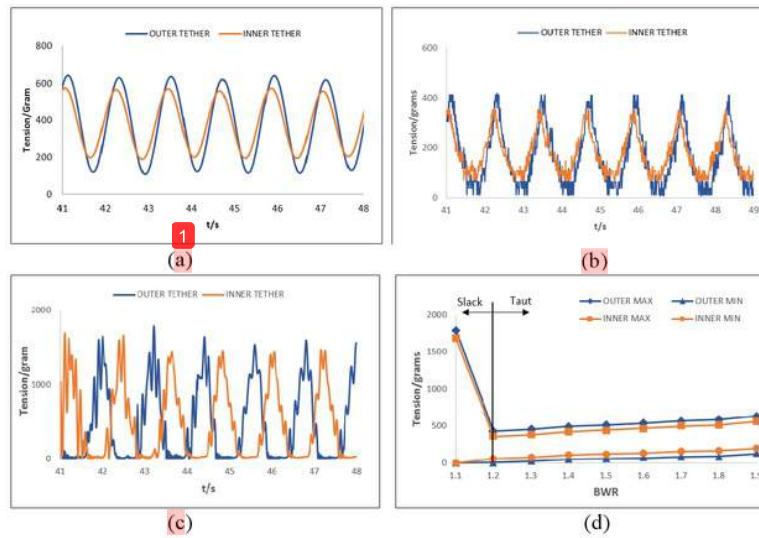
Figure 6 Time series of SFT tether tension force: (a) BWR = 1.9; (b) BWR = 1.2; (c) BWR = 1.1; (d) maximum and minimum tether tension force (significant wave)
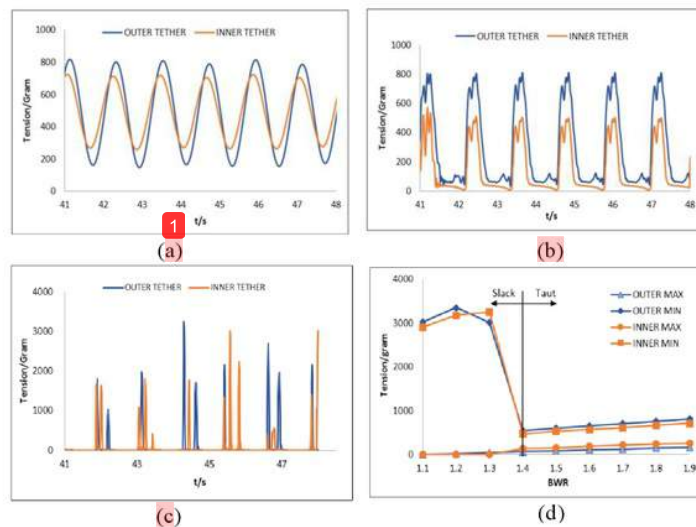
Figure 7 Time series of SFT tether tension force; (a) BWR=1.9; (b) BWR=1.4; (c) BWR =1.3;(d) maximum and minimum tether tension force (individual wave)

4.   DISCUSSION

The most significant threat to the stability of an SFT moored by cables is the occurrence of slack (Forum of European National Highway Research Laboratories, 1996). Cables in such structures are highly resistible to tension and hardly able to take compression (Gimsing, 1983).Under severe wave conditions, impact force occur when a horizontal cylinder structure is imposed on the wave (Sundar, 1994). BWR value is one of the structural parameters that can cause cable slack to occur. Because of this correlation, the current experiment sought to define the relationship between BWR value and slack occurrence.

In the present experiment, every BWR value generated a different time series of tether tension: harmonic, periodic or impulse tension forces. In the event of a significant wave when the BWR value was high (i.e., 1.9), the time series of the SFT tether tension force was harmonic. The dynamic response of the tether tension changed to periodic when the BWR value was 1.2. Slight slack on the tether began to appear when the BWR value was 1.1. Different results were observed with individual waves, where the results obtained showed that when the BWR value was high (i.e., 1.9), the time series of the SFT tether tension force was still harmonic. The dynamic response of the tether tension changed to periodic when the BWR value was 1.4, and tether slack occurred when the BWR value was 1.3. The value of the BWR parameter depended on the amount of functional load, such as that of the pipeline and its contents (see Table 3). Thus, if the weight of the pipeline and its contents are accounted for correctly, the maximum pipeline weight that can be installed without triggering slack and snap loading in the SFT cable can be determined.

Calculations of the maximum pipeline weight for the SFT were carried out by scaling the experimental results to a real environment at a dimension scale of 1:100.

Table 3 Pipeline properties

Diameter of steel (dst)	404.4	mm
Thickness of steel (t)	14.3	mm
Thickness of corrosion coating (tcc)	5.5	mm
Density of steel (ρst)	7850	kg/m^3
Density of corrosion coating (ρcc)	1280	kg/m^3
Density of content (ρi)	750	kg/m^3

The calculations shown in Tables 4 and 5 illustrate the process for obtaining the maximum weight at which a pipeline and its content may be placed in the SFT. In the event of a significant Java Sea wave in the hundred-year return period, per the calculations shown in Table 4, the maximum acceptable weight of a pipeline and its contents is approximately 534 tons. For a safety factor of 1.5, a maximum of eight pipeline pieces may be placed in the SFT.

Table 4 Calculation of maximum pipeline weight per a significant wave in the hundred-year return period

Load History	Weight of SFT (Ws) (tons)	SFT buoyancy (b) (tons)	Value of BWR	Weight of pipeline (Wp) (kg/m)	Weight of ballast(Wb) (kg/m)	Max pipeline number (SF=1.5) (n)
Installation	1333.5	2241	1.2	22.644	534	15
Hydro test	1333.5	2241	1.2	39.872	534	8
Operational pristine	1333.5	2241	1.2	35.565	534	10

In the event of an individual Java Sea wave in the hundred-year return period, the maximum allowed weight for a pipeline and its contents is approximately 267.214 tons (see Table 5). For a safety factor of 1.5, a maximum of four pipeline pieces may be placed in the SFT.

Table 5 Calculation of maximum pipeline weight per an individual wave in the hundred-year return period

Load history	Weight of SFT (Ws) (tons)	SFT buoyancy (b) (tons)	Value of BWR	Weight of pipeline (Wp) (kg/m)	Weight of ballast (Wb) (kg/m)	Max pipeline number (SF=1.5) (n)
Installation	1333.5	2241	1.4	22.644	267.214	7
Hydro test	1333.5	2241	1.4	39.872	267.214	4
Operational pristine	1333.5	2241	1.4	35.565	267.214	5

5. CONCLUSION

This study examined the concept design for a submarine pipeline using an SFT for use in the oil and gas industry. A supportive experiment was carried out to investigate the parameters at which tunnel stability is put at risk due to tether slack. Based on data from a previous study of Java Sea waves from a hundred-year return period at the IHL-BPPT, two wave cases (significant and individual) were investigated and tested in the laboratory. The results of the present study show that more pipeline can be placed in the SFT if data from a significant Java Sea wave is used during the tunnel's design than if the design is based on data from an individual Java Sea wave. However, because both conditions have economic and safety-related consequences, combined use of the data from both individual and significant waves is advised when applying the concept. For example, it is recommended that significant wave data be used to place the pipeline in the SFT structure, while individual wave data be used to design a stronger tether to protect against the threat of snap force. Based on this recommendation, for the future research, it is necessary to investigate the proper combination of buoyancy weight ratio (BWR) and property of tether parameter to avoid snap force occurrence.

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