Dynamic Behavior of Water Intake Riser for Ocean Thermal Energy Conversion System

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ABSTRACT

Renewable energy has been regarded as an alternative to generate electricity. One of the examples for this energy is the Ocean Thermal Energy Conversion (OTEC) system which harnesses the temperature difference between sea surface and deeper ocean layer. Most research on OTEC is related to system efficiency but does not address the behavior of subsystem such as its water intake riser (WIR). Thus, this research aims to identify the dynamic behavior of water intake riser in terms of its vertical displacement and tension in order to investigate the sensitivity of key parameters of water intake riser design. The study covers the dynamic behavior of a derived mathematical model with reference to its vertical displacement and tension ratios result in which the length of the riser needs to be suitably designed particularly during the riser excitation period. A stiffer material of the riser has to be selected to obtain small vertical displacement and tension ratios while the diameter of the WIR only needs to be taken into account if the efficiency of the OTEC is of major concern. This study could aid in designing the suitable WIR to be implemented for the OTEC system.

Keywords: *Water intake riser, ocean thermal energy conversion system, dynamic behavior*

1.0 INTRODUCTION

Many countries have been developing the urge to find and research for renewable and carbon-free energy resources as an alternative to the fossil fuel. One of the renewable energy resources extracted from the ocean is the Ocean Thermal Energy Conversion (OTEC) system. OTEC is used to generate electricity indirectly from solar energy by using the principle of the natural temperature difference between the warm surface of the ocean and the colder seawaters in the deeper layers.

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The temperature difference must be approximately greater than 20°C to effectively support the operation of an OTEC facility net power generation [1]. This requirement is met by the tropical ocean which also has large areas of collecting and storage capacities needed to harvest solar radiation [2]. In a closed-cycle system, warm seawater heats a working fluid, such as ammonia with which has a low boiling point [3]. The resulting vapor rotates a built-in turbine to drive a generator. Later, the vapor is condensed by cold seawater and cycled back through the system. On the other hand, in an open-cycle OTEC, warm seawater is pumped into a vacuum chamber where it is flash evaporated and the resulting steam turns the turbine to rotate [2]. Cold seawater is used to condense the steam into the water before it is later returned to the environment.

As an essential part of its operation, an OTEC power plant delivers large amounts of cold seawater from the deeper layers of the ocean through a long water intake riser (WIR) suspended from the OTEC platform [4]. As illustrated in Figure 1, for a plant generating 40 MW of electric power, the water intake riser can be as large as 9.2 m in diameter and 1000 m in length [4]. When it is installed in the ocean environment, the WIR will experience a series of combined load, including hydrodynamic forces and host platform motions. Moreover, current, wind and free-surface waves represent important ambient flow conditions [5].

WIR has become a research interest in the offshore industry as they are able to convey a large amount of cold seawater from the deeper ocean layers. The WIR conceptually needs to extend from the host vessel down to nominally 1000 m below sea level to reach a low-temperature water layer at approximately 5 °C depends on the application of the riser. A commercial-scale OTEC plant requires a pipe diameter of about 4-10 m with a length of 1000 meter [6]. The configuration of the riser is also different. For a single configuration, it is easier to install [7]. However, because of its large diameter and high flow rate, the WIR present unique design challenges and performances uncertainties [8]. An OTEC project known as Sagar Shakti [9] was abandoned because of problems that crept in while deploying the pipe to the platform [10].

This paper discusses the sensitivity of the vertical displacement and tension ratios of the WIR from the perspective of excitation period, length, diameter, and material of riser, which can provide a reference to the further implementation of OTEC system.

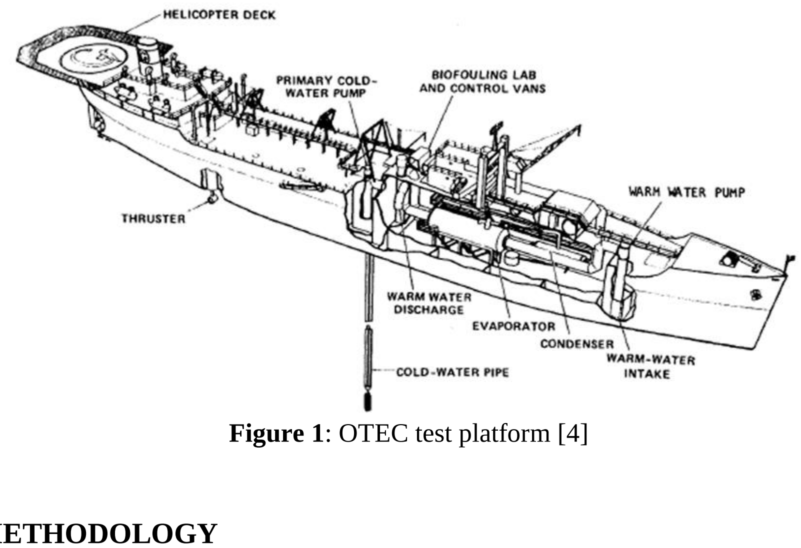


Figure 1: OTEC test platform [4]

2.0 METHODOLOGY

2.1 Theoretical Modeling

In order to understand the dynamic behavior of the WIR, the vertical displacement and tension of the riser are being identified. There are similarities between the axial vibration of fixed-risers and hung-off risers [11] where WIR is treated as a hung-off riser in the theoretical modeling. Sparks [11] had presented an equation to describe the axial displacement at distance *x* from the top of the riser. This equation is applicable to the free hanging WIR as it is treated as hung-off riser with a concentrated mass *M* at the lower end of the riser, which is stated as:

$$u_{x,t} = U_0 \frac{\cos\left[\omega\left(L' - x\right)/c\right]}{\cos\left(\omega L'/c\right)} \sin \omega t \tag{1}$$

where $u_{x,t}$ is a dynamic vertical displacement at distance *x* of the riser in m; U_o is a top-end sinusoidal movement of amplitude in m; ω is an excitation frequency in rad/s; L' is an equivalent length of the riser in m; and *c* is a celerity (speed of transmission of axial stress waves in the riser) in m/s. A dynamic tension $T_{x,t}$ at distance *x* from the top of the hung-off riser equation is defined as [11]:

$$T_{x,t} = mc\omega U_0 \frac{\sin\left[\omega\left(L' - x\right)/c\right]}{\cos\left(\omega L'/c\right)} \sin \omega t \tag{2}$$

where *m* is a mass per unit length of the riser in tonne/m.

2.2 Numerical Simulation

To identify and determine the sensitivity of each key parameter on the WIR, the vertical displacement ratio, $u_{x,t}/U_o$ and tension ratio, $T_{x,t}/mc\omega U_o$ were studied through a numerical analysis. There is a need to carefully tune the related parameters considering a single variable at a time to obtain an accurate result. The four variables that need to be parametrically tuned to observe their effects and can be regarded as case studies are:

A. Excitation period of the WIR, $2\pi/\omega$
B. Length of the WIR, L'
C. Diameter of the WIR, *d*
D. Material of the WIR

In Case A, the parameter to be studied is the excitation period $2\pi/\omega$. For Case B, the parameter of interest is the length L' of the WIR. The excitation period is also being identified according to the selected geographic locations which are the south waters of North Sulawesi with 1.5 - 2.5 m of wave height [12], north part of the North Sulawesi with 3.5 m wave height [12] and Terengganu offshore with a wave height of up to 1.2 m [13]. Case C is concerned about the effect of the diameter *d* of the WIR due to its significance in delivering sufficient amount of seawater to the OTEC system. In Case D, the parameter to be investigated is the material of the WIR. Two types of materials to be analyzed are the high-density polyethylene (HDPE) and fiber-reinforced plastic (FRP). Table 1 shows the testing case matrix of the parameters for numerical simulation.

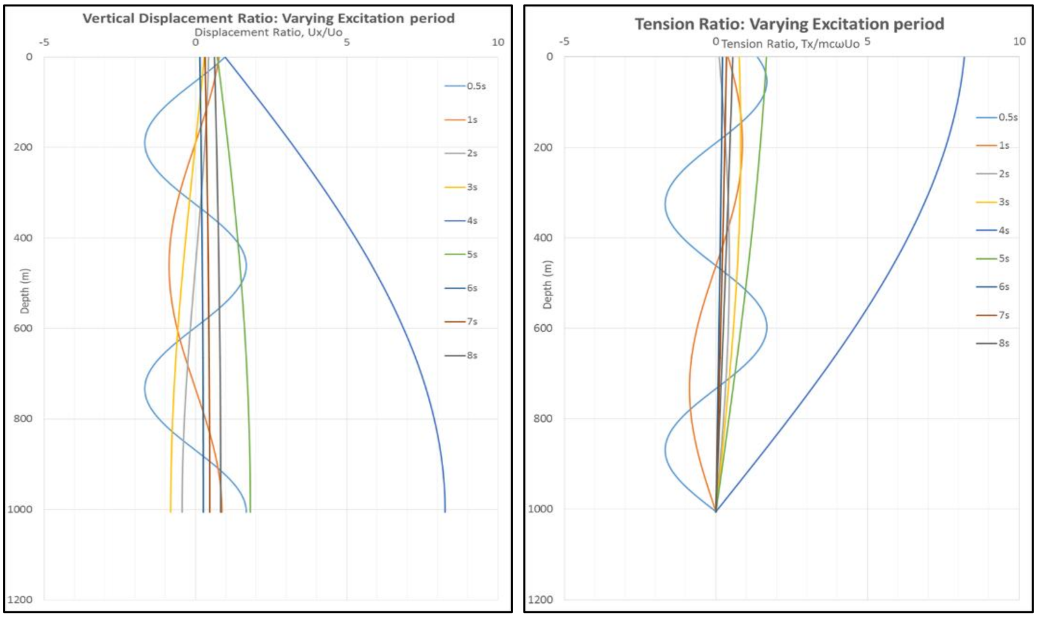
Table 1: Test case matrix for numerical simulation

Parameter	Case					
	A	B			C	D
		a	b	c		
Excitation period (s)	**0.5 - 8**	5.083	6.630	3.882	6.630	6.630
Length (m)	1000	**500 - 1300**			1000	1000
Diameter (m)	4.2	4.2			**4.2 - 10**	4.2
Material	HDPE	HDPE			HDPE	**HDPE, FRP**

3.0 RESULTS AND DISCUSSION

3.1 Case A: Excitation Period of The WIR

For a WIR to be installed, the excitation period $T = 2\pi/\omega$ is of significant interest. The reason being, there is a need to avoid the riser to be excited at a period that will create a huge magnitude of the vertical displacement ratio $u_{x,t}/U_o$ and tension ratio $T_{x,t}/mc\omega U_o$. This is related to the vertical amplitude at the top-end of the riser. If the magnitudes of the vertical displacement ratio and tension ratio are large, then the vertical displacement and tension at distance x from the top of WIR will have to be multiplied with whatever amplitude at the top-end of the riser. Another factor to be considered in installing the WIR considering the excitation period is the mode type related to the behavior of the WIR itself. There is also a need to minimize high-order modes due to multi-directional deformation of the vertical displacement as it will affect the riser to have a shorter fatigue lifespan. Eliminating the undesired excitation period, the riser is then left with excitation period range from 5 – 8 s as can be seen in Figure 2. This implies that the WIR, in this case, can be installed at the particular range of the excitation period.



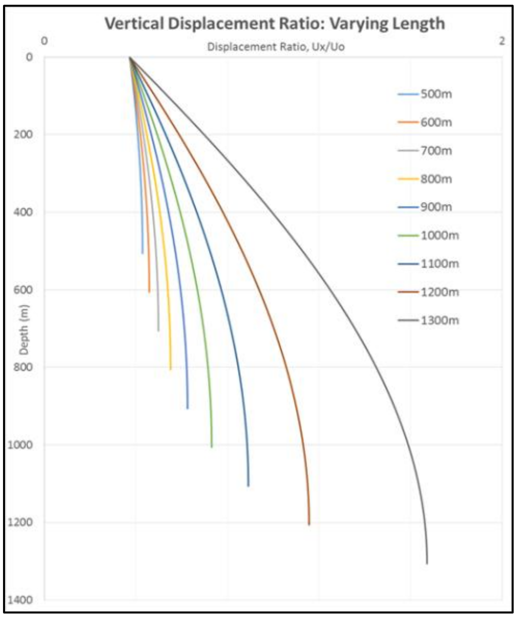
(a) (b)

Figure 2: Varying the excitation period for (a) vertical displacement ratio and (b) tension ratio

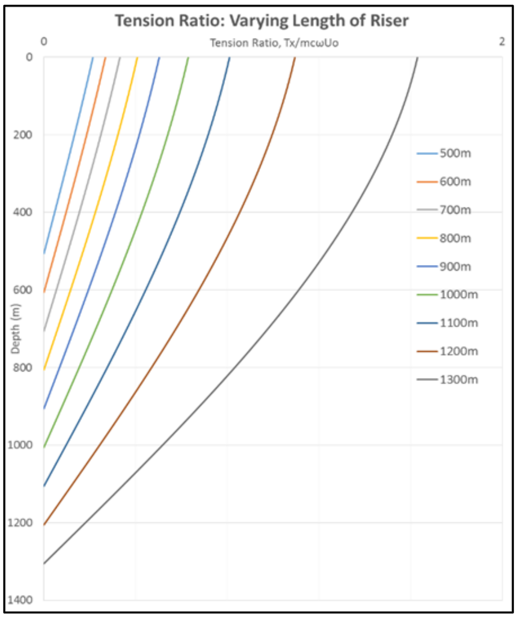
3.2 Case B: Length of The WIR

For the first location, the riser is excited at the south water of North Sulawesi sea with an excitation period of 5.083 s. In Figures 3(a) and (b), the riser shows the same behavior, in general, with different magnitudes. The vertical displacement ratio $u_{x,t}/U_o$ and tension ratio $T_{x,t}/mc\omega U_o$ of the WIR can then be the deciding factor for a selection of the length L' for the riser. Although the WIR is supposedly to be long enough to extract the cold water with enough temperature difference for the system, there must be a cost consideration in doing so. If the magnitudes of the vertical displacement ratio and tension ratio are large enough as to make vertical displacement and tension considerably large, this could be an important additional factor to select a shorter riser. For the second location, the riser is excited at the north part of North Sulawesi sea with an excitation period of 6.630 s. In Figures 3(c) and (d), the riser also shows the same behavior with a smaller difference in the magnitude compared to the riser that is excited at the south water of North Sulawesi.

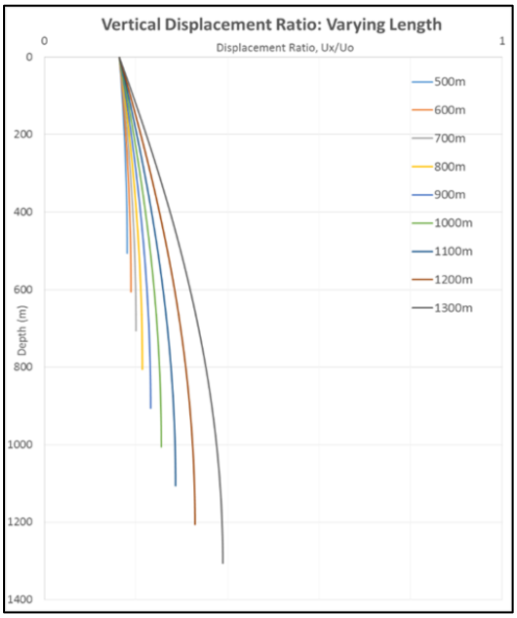
This means that the WIR is more preferably to be installed at the second location as its behavior is less vigorous. For the third location, the riser is excited considering the sea condition of the Terengganu offshore with an excitation period of 3.882 s. In Figures 3(e) and (f), the risers unexpectedly show different behavior. Regarding the magnitudes of the vertical displacement and tension ratios, risers with a length of 1000 m and longer exhibited larger magnitude of the ratios. However, it is noteworthy that the actual water depth at the Terengganu offshore is relatively shallower and far less than 1000 m. The results show that even if the Terengganu offshore has a water depth of over 1000 m, the maximum appropriate riser length for the location is only 900 m. Under some deep water conditions, the riser also exhibits a negative ratio, which means that the riser will behave oppositely to the direction of the amplitude at the top-end of the riser.



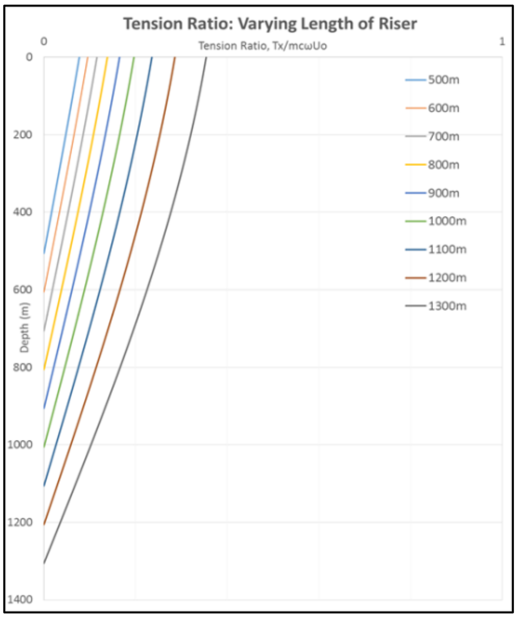
(a)



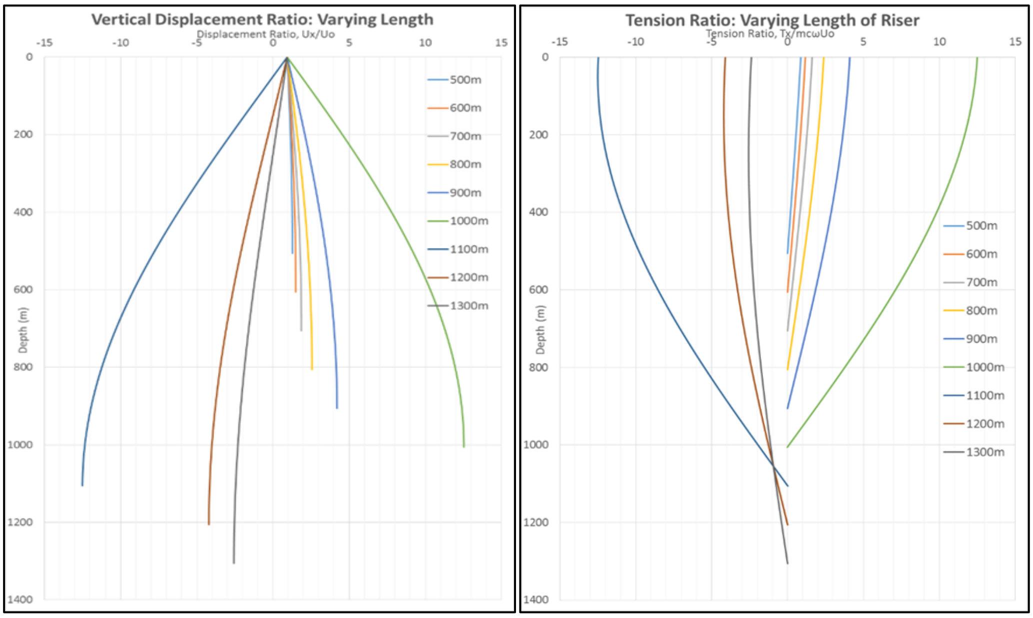
(b)



(c)



(d)

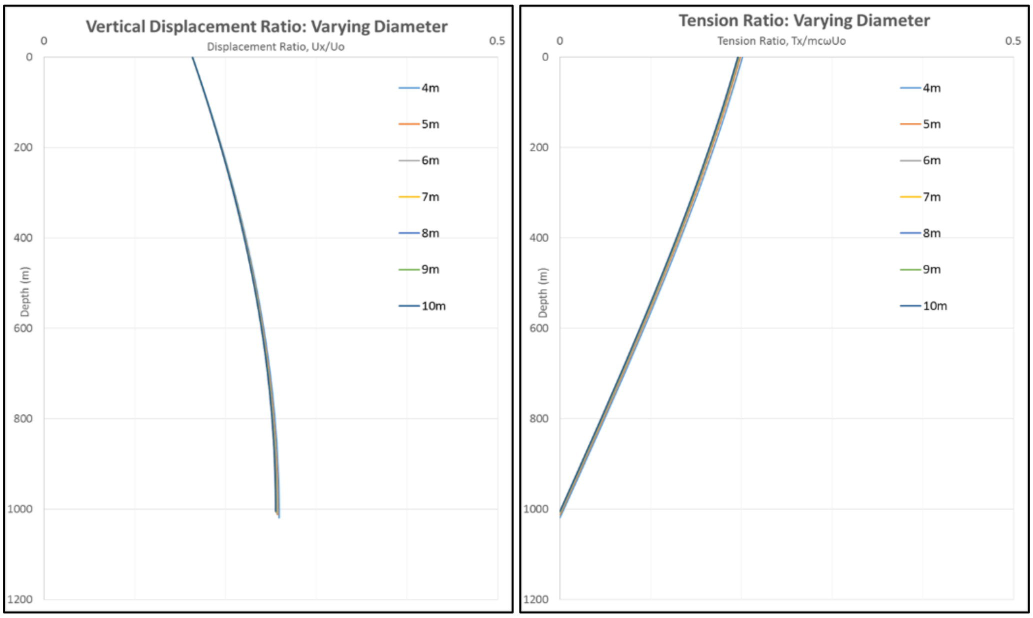


(e) (f)

Figure 3: Varying the excitation lengths for (a) vertical displacement ratio & (b) tension ratio at the southern part of North Sulawesi (c) vertical displacement ratio & (d) tension ratio at the northern part of North Sulawesi (e) vertical displacement ratio & (f) tension ratio at the Terengganu offshore

3.3 Case C: Diameter of The WIR

In Figure 4, the riser exhibits almost identical behavior regardless of the change of its diameter from 4 m to 10 m. It can be shown that the diameter *d* of the riser has no significant role in determining the vertical displacement ratio $u_{x,t}/U_o$ and tension ratio $T_{x,t}/mc\omega U_o$ of the riser. However, the diameter of the riser still needs to be considered when dealing with the flow rate of cold water. The diameter of the riser is also significant to be considered as it has an effect on the heat friction loss for the overall functionality of the OTEC system. However, this part is out of the scope of discussion in this paper.

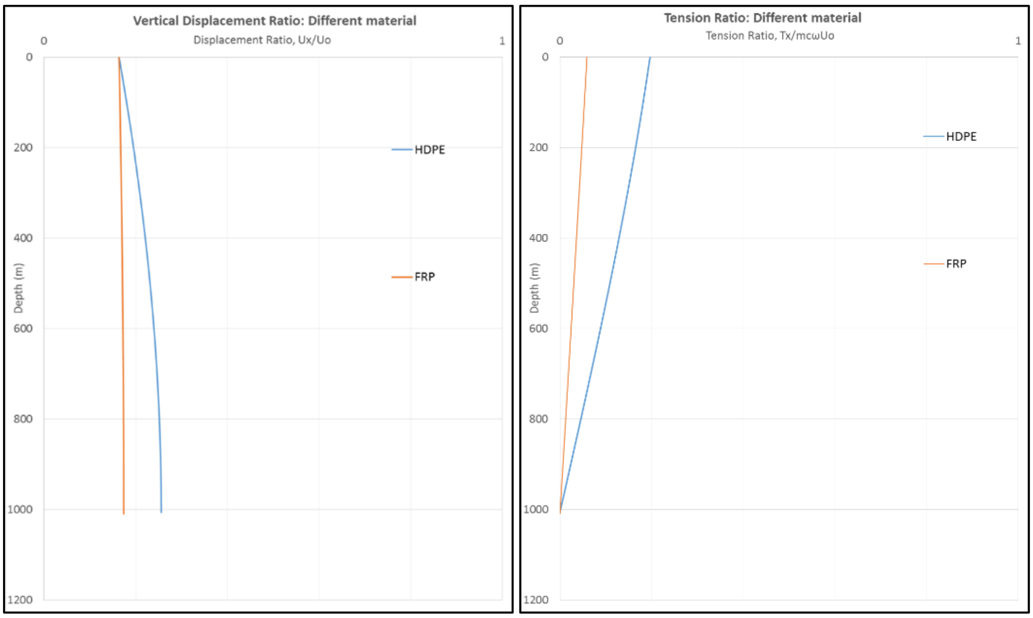


(a) (b)

Figure 4: Varying the diameter for (a) vertical displacement ratio and (b) tension ratio

3.4 Case D: Material of The WIR

Figure 5 shows that the risers made of different materials behave differently. This is due to the different celerity *c* caused by different materials. A higher value of celerity corresponds with a higher stiffness value. In this case, FRP is stiffer than HDPE. The vertical displacement ratio $u_{x,t}/U_o$ and tension ratio $T_{x,t}/mc\omega U_o$ of the FRP are also smaller than the HDPE counterpart and hence the former is more suitable for the construction of a WIR.



(a) (b)

Figure 5: Varying the diameter for (a) vertical displacement ratio and (b) tension ratio

4.0 CONCLUSION

Based on the vertical displacement and tension ratios result, the length of the riser needs to be appropriate and suitable for the excitation period in which the riser is caused to excite. A stiffer material of the riser needs to be selected to obtain smaller vertical displacement and tension ratios while the diameter of the water intake riser only needs to be taken into account if the efficiency of the OTEC system is of major concern.

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