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On the two essential concepts for SFT: synergetic buoyancy-weight ratio and slack-taut map

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Abstract

In the submerged floating tunnel (SFT) design and future construction, buoyancy-weight ratio (BWR) and slack-taut performance (STP) are two intrinsic issues with respect to the SFT dynamic response and stability under the structural and external loadings. BWR is defined as the ratio of tunnel buoyancy to the whole tunnel weight. Our experiments and numerical simulations indicate that BWR dominates the dynamic response of SFT and is the most important parameter to be considered in SFT design. For this, we re-state the essential concept of "Synergetic range of BWR". This is regarded as, for an SFT structure with related environmental conditions, a suitable range of BWR value exists, which will lead to less dynamic response and more stable for the SFT. STP is the tether slacking and the related snap force under sea wave conditions. Our simulation results show that SFT tether may go slack and induce snap force at a large wave height at a certain combination of BWR and inclined morning angle (IMA) of the tether. As the second essential concept for SFT, a Slack-Taut Map of SFT is constructed, which describes the occurrences of slack and snap force (under a certain wave condition) as a function of BWR and IMA.

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Keywords: Submerged floating tunnel; buoyancy-weight ratio; slack-taut map; inclined mooring angle; snap force.

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1. Introduction

When mankind intends to cross a vast lake, strait or ocean of a large water depth, the transportation means of traditional bridges and tunnels are no longer possible, and the speed of watercrafts is too slow to meet the requirement. To cross vast water ways with a fast speed is the dream of mankind, and submerged floating tunnel (SFT) will make

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the realization of this dream.

SFT, also named Archimedes Bridge, is a structural passage located in between the water surface and the water bed (a certain distance under water surface), which is floating by the aid of buoyancy and tethered to the water bed and the shore. SFT is an innovative and promising technology for future crossing straits, lakes and rivers available for vehicles and high speed trains [1,2].

Comparing with traditional bridges and tunnels, the unique feature of SFT is that it efficiently takes the advantage of the nature force – buoyancy – to support its weight and traffic load. Therefore, SFT has the distinctive superiorities: environment-friendly, wide applicability and high economic effectiveness [3,4]. However, there is still not an actual SFT being built in the world, which is ascribed to two reasons, namely the feasibility in technology and the acceptability in publicity due to relevant safety concern.

The structure type and the loading style that an SFT is subjected to are much different from the cases of the bridges above the water and the tunnels embedded in the foundation. An SFT presented in the conceptual or structural design normally contains 4 parts: tunnel structure, shore connection structure, tether system and foundation structure [1,2]. The integrity of an SFT is inevitably subjected to the environmental load and the traffic load. The structural parameters of an SFT and its reaction to the dynamic load are the key points in the SFT design, which will affect the stability and safety of the structure [5,6]. For these, there are two essential issues that play extremely important roles in the dynamic response of an SFT due to internal and external loadings. The first essential issue is the buoyancy-weight ratio (BWR) and the second one is the slack-taut performance (STP) of an SFT.

BWR is the ratio of tunnel buoyancy to the whole tunnel weight. For an SFT, BWR influences not only the tunnel geometrical design but also material selection, strength design, stiffness design, etc. It is undoubtable that tunnel buoyancy must be larger than its self-weight and the net buoyancy (the difference between buoyancy and self-weight) is balanced by the tether system which is connected between tunnel and foundation. Obviously, BWR determines the tension force of the tether and influences the dynamic behaviour of SFT structure [1,5,7,8]. In addition, under the service, the actual BWR value of SFT is affected by traffic and crowd load.

The dynamic responses of SFT tethers are of three types: taut, slight slack and evident slack with snap force in the tether. STP is the process of an SFT subjected to severe environmental conditions such as huge waves, earthquakes, etc. under which SFT tethers may go slack and backward. It is obvious that the tether is just resistible to tension and cannot sustain compression. When the motion of SFT becomes large, the tension of SFT tethers may reduce to a low level, and the tethers may become slack. In the cases of periodical excitation such as wind-induced wave, the tether will behave in the way of alternating slack and taut. It is vital that the tether becomes taut from slack state, and thus it may produce very high tension in the tether resulted in a “snap force” due to its impact effect [8–12].

In this paper, we summarize our recent results on the two issues of BWR and STP. For the former, our simulations show that BWR is a key structure parameter with respect to structural stability [5]. Further, our numerical simulations and experiments indicate that BWR dominates the dynamic response of SFT and is the most important parameter to be considered in SFT structural design [8]. For this, we re-state the concept of “Synergetic range of BWR” [1]. For an SFT under related environmental conditions, there exists a suitable range of BWR value which will lead to less dynamic response and more stability for the SFT. Regarding STP, our results show that the response of SFT tether tension is more sensitive to wave height compared with wave period, and both BWR and inclined mooring angle (IMA) have substantial influence on the occurrence of slack in SFT tether. As a consequence, a Slack-Taut Map (STM) of SFT tethers is constructed at the given wave condition, which intuitively describes the occurrences of slack and snap force with different combinations of BWR and IMA [8]. Thus, STM is confirmed as the second essential concept for SFT.

2. Effects of BWR on SFT dynamic responses

In the design of an SFT, to select an appropriate value of BWR is a key point. On the one hand, the value of BWR should be sufficiently large to provide enough net buoyancy. On the other hand, the stress sustained by the tethers will increase with the increasing of BWR, which will cause potential threat to the safety and increase the cost of tether system.

First, the dynamic response of the tunnel tube for an SFT with different values of BWR is analysed and simulated. Fig. 1 is the simulation results for the dynamic responses of the SFT tunnel tube with different values of BWR under hydrodynamic loadings [5], which is expressed in terms of STDEV/D versus BWR, where STDEV is the standard deviation of tunnel displacement (or amplitude of tunnel vibration) and *D* is the tunnel diameter. For the dynamic response in current direction, the value of STDEV for the SFT tunnel tube increases with the increasing of BWR (Fig. 1(a)). For the response in vertical direction, the value of STDEV decreases dramatically with the increase of BWR between 1.1 and 1.2 (Fig. 1(b)). When BWR continues to increase, the vertical response decreases very slowly.

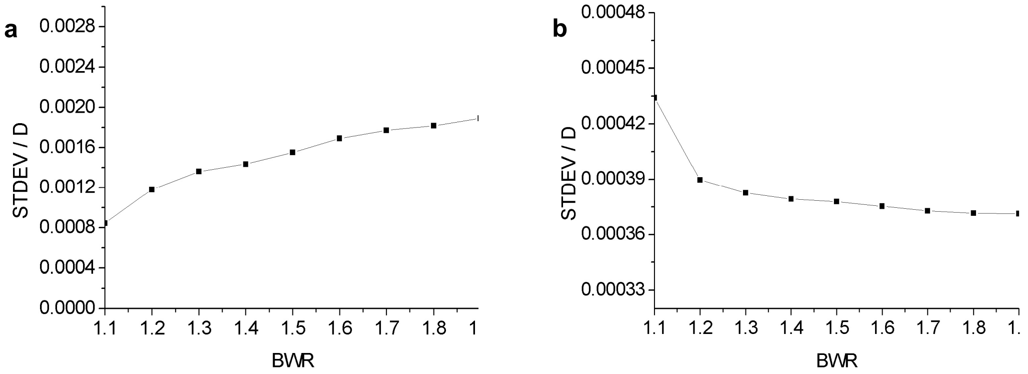

Fig. 1. STDEV/*D* at SFT mid-span under different BWRs, (a) current direction; (b) vertical direction [5].

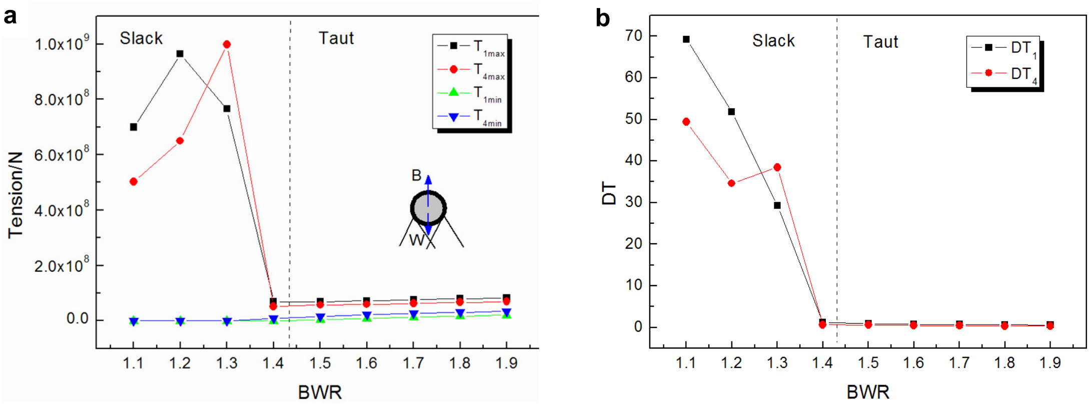

Fig. 2. (a) The maximum and minimum tension force versus BWR; (b) Variation of specific dynamic force versus BWR [8]; subscript 1 denoting the outer tether and subscript 4 denoting the inner tether shown in the schematic in (a).

Secondly, the dynamic response of the tether system for an SFT with different values of BWR is analyzed and simulated. In this simulation the values of BWR range from 1.1 to 1.9 and the IMA is at a given condition. Fig. 2(a) is the results showing the variation of the maximum tension force and the minimum tension force of tethers 1 and 4 as a function of BWR [8]. It is seen that when BWR<1.4, the maximum tension force is remarkably large resulted from the tether slack. When BWR>1.4, the tether slack diminishes and the maximum tension force reduces to a low level, which together with the minimum tension force slightly increases with the increasing of BWR value.

A parameter *DT*, namely specific dynamic tension force, is introduced to describe the effect of BWR on the tether response to the loading, for which the initial tension force is deducted from its maximum value, i.e.

$$DT = \frac{T_{\max} - T_0}{T_0} \tag{1}$$

where T_{max} is the maximum tension force and T_0 is the initial value. It is evident that the value of DT indicates the increment of tension force with respect to the initial state. Fig. 2(b) shows the variation of DT as a function of BWR. When BWR is between 1.1 and 1.4, the value of DT is from as high as 70 down to about unity, which is due to the occurrence of slack process, indicating that the increment of the tension force in the BWR range from 1.1 to 1.4 is so large that it will cause unexpected failure. When BWR is between 1.4 and 1.9, the value of DT is stable of about the magnitude of unity reflecting the state of no slack occurrence, which implies that the increment of the tension force is no more than its original value in the BWR range between 1.4 and 1.9.

As an important factor, the natural frequency was estimated by both theoretical calculation and experimental measurement. Fig. 3 demonstrates the results of natural frequency for the SFT tube versus BWR for IMA = 33.65° (Fig. 3(a)) and versus IMA for BWR = 1.4 (Fig. 3(b)) [13]. From Fig. 3 (a), it is seen that both results via experiment and calculation are close each other although the experimental one is slightly large, with the experimental results of natural frequency increasing from 0.38 to 0.83 Hz against the BWR ranging from 1.190 to 3.336. Fig. 3(b) shows that the natural frequency increases with the increasing of IMA. For IMA between 0 to 41°, the value of natural frequency increases from 0.27 to 0.64 Hz. It should be emphasized that the characteristics of self-vibration for the SFT tube is a basic factor in relation to the SFT dynamic response to the external loadings.

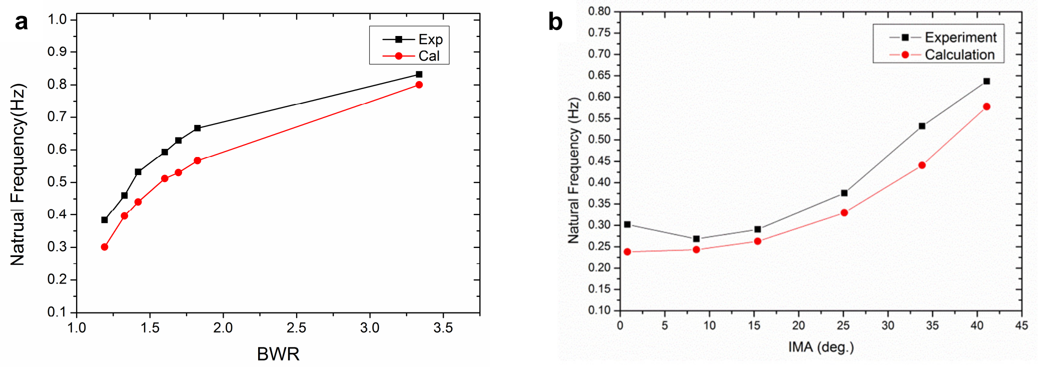

Fig. 3. Experimental and numerical results of natural frequency as a function of BWR (a) and IMA (b) [13].

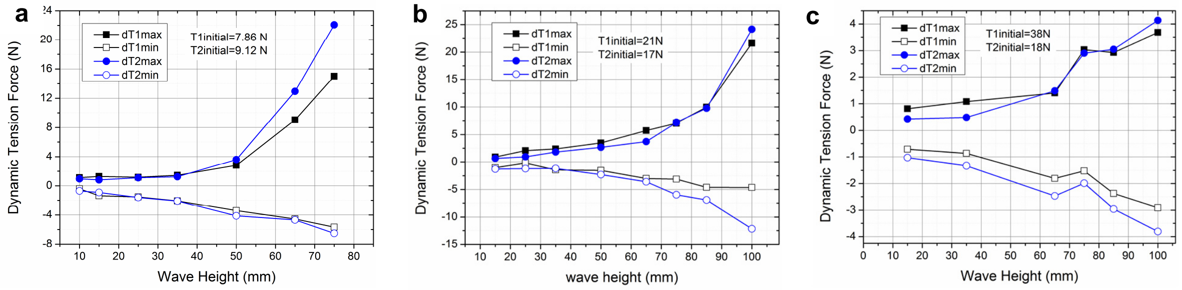

Fig. 4. Experimental results of the maximum and the minimum dynamic tension of tether as a function of wave height [13]; (a) BWR=1.2, IMA=33.65°; (b) BWR=1.4, IMA=33.65°; (c) BWR=1.6, IMA=15.20°.

Fig. 4 presents the experimental results of 3 cases of the maximum and the minimum dynamic tension acting on a pair of tethers as a function of wave height, where dynamic tension is defined as $T–T_0$ with T being the tension at a given stage and T_0 being the initial tension. For the case of BWR=1.2, IMA=33.65° (Fig. 4(a)), when wave height is less than 50 mm, both the maximum and the minimum dynamic tension are of slightly changes with the increasing of wave height; and when wave height is beyond 50 mm, the minimum dynamic tension keeps slightly downward and approaches to its initial value, but the maximum dynamic tension increases remarkably with wave height, which is the result of tether slack induced impact force. For the case of BWR=1.4, IMA=33.65º (Fig. 4(b)), when the wave height is less than 65 mm, both the maximum and the minimum dynamic tension are of slightly changes with the increasing of wave height; when the wave height is beyond 75 mm, the minimum dynamic tension keeps downward and approaches to its initial value, but the maximum dynamic tension increases remarkably with wave height, which is again due to the trigger of tether slack. For the case of BWR=1.6, IMA=15.20º (Fig. 4(c)), the situation is different from the previous two cases; both the maximum and the minimum dynamic tension are just of linear and slight changes with wave height. Note that the maximum absolute values for the dynamic tension at the wave height of 100 mm are less or about 4 N, which is only 10% of the initial value for T1 tether and 23% of the initial value for T2 tether, implying that no slack process exists for this case.

The effect of BWR on the dynamic response of SFT tube was also experimentally investigated and the test condition was BWR: 1.2–1.8, IMA: 33.65º, wave period: 2s, and wave height: 10 mm, 25 mm, 50 mm and 75 mm. The results were expressed in terms of dimensionless response amplitude as a function of BWR. The dimensionless response amplitudes in *X* (or current) direction U_x and in *Y* (or vertical) direction U_y are defined as

$$U_x = \frac{rms(x)}{R} \quad and \quad U_y = \frac{rms(y)}{R} \tag{2}$$

where *rms* is the mean square root of displacement and *R* is the radius of the model tube, which is 80 mm in the model test.

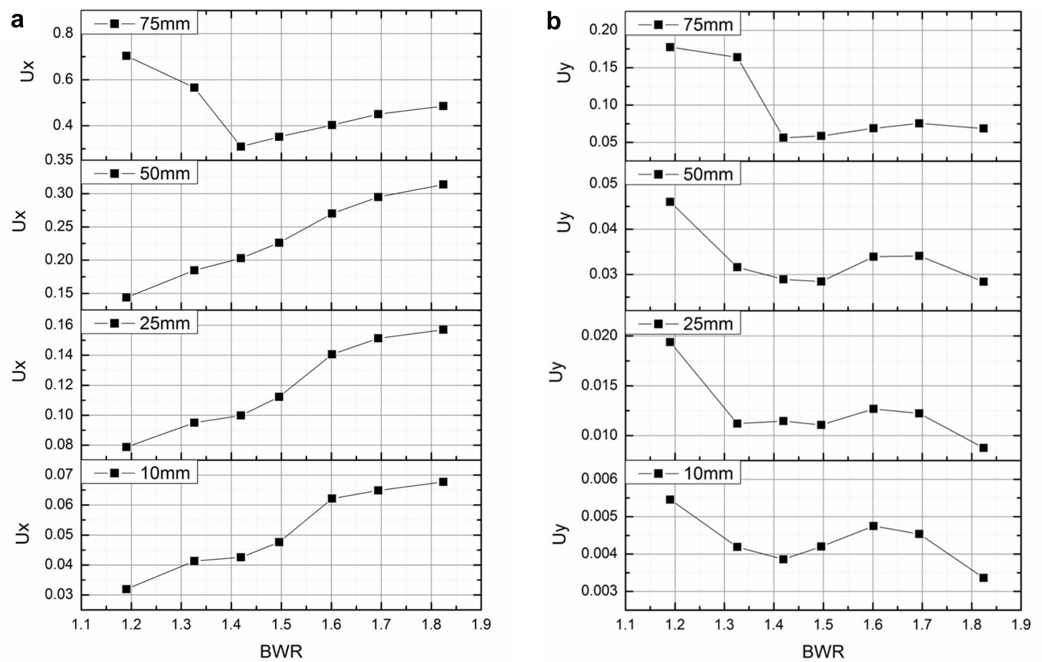

Fig. 5. Experimental results of dimensionless response amplitude of SFT tube under different wave heights as a function of BWR [13]; wave period = 2s, IMA = 33.65º; (a) current direction; (b) vertical direction.

Fig. 5 presents the experimental results of U_x and U_y as a function of BWR under different wave heights. When wave height is from 10 mm to 50 mm, the value of U_x linearly increases with the increasing of BWR (Fig. 5(a)). When wave height is 75 mm, the variation of U_x with BWR is no longer a linear trend but is of a downward and then upward style with a turning point at BWR = 1.4. The value of U_x is substantially large at the lower end of BWR (≤ 1.3) and it has a minimum value at BWR=1.4. This variation tendency of U_x with BWR at different wave heights is apparently attributed to the occurrence of slack at the couple condition of large wave height and low BWR value. For the case U_y (Fig. 5(b)), with the increase of BWR, its value decreases first, then almost keeps constant and slightly goes down further. Note that for BWR = 1.4~1.8, the trend of U_y with BWR is stable and of a relatively small value.

3. Effects of STP on SFT dynamic responses

Under external loadings, an SFT tube will be moving more or less accordingly. When the amplitude of the movement for an SFT tube exceeds a critical value, the tension force will be equivalent to the distributed dragging force within the tether. At this moment, the phenomenon of slacking will happen [8,10]. The process of tether slacking for an SFT is commonly of an oscillating feature due to the cyclic external loadings, which will inevitably cause the repeating slack-taut situation. At a certain frequency of slack-taut process, a large tension force acting on the tether will occur, which is called snap force [8-10].

It is obvious that the occurrence of tether slack-taut process is closely related to the states of BWR and IMA for an SFT. Thus, we calculate various combinations of BWR and IMA to give the results of slack-taut performance (STP) for BWR ranging from 1.1 to 1.9 and IMA ranging from 0 to 45°. The results are illustrated in Fig. 6 and we call this Slack-Taut Map (STM), which is another essential concept for SFT. As described previously, the states of tether STP are characterized as 3 categories: taut, slight slack and evident slack with snap force in the tether, which are accordingly expressed in Fig. 6.

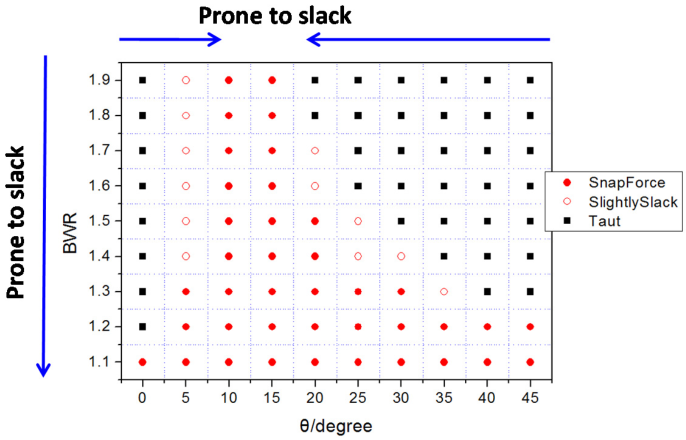

Fig. 6. Constructed slack-taut map of SFT based on simulation results (wave height: 12 m, and wave period: 15 s) [8].

It is clearly seen from Fig. 6 that the tether STP is sensitive to the states of BWR and IMA of SFT, and the effect by these two factors are coupled. When the value of IMA is substantially small (close to 0), the slack process is unable to occur except for the small value of BWR. When BWR is large, the range of IMA to cause snap force is narrow, which is around an IMA of 10°, and the range will go wider as BWR decreases. When BWR is as small as 1.1, slack process will occur in all the cases. The constructed STM explicitly shows the affecting trend of BWR and IMA. It indicates the slack area with respect to the key structure parameters of BWR and IMA under the specified wave condition, which provides a foundation for future SFT design. The results obtained by the present simulations show a good agreement with the observations about the tether dynamic tension in the model experiments [7,14].

Fig. 7 is an alternative demonstration of STM as a result of critical wave height analysis that is defined as the wave height at which the slack will occur under the given combined state of BWR and IMA. It is seen from Fig. 7 that the coupled effects of BWR and IMA on STP is in consistent with those indicated in Fig. 6.

Fig. 8 shows the variation of critical wave height as a function of IMA at 4 states of BWR: 1.2, 1.4, 1.6 and 1.8. It is implied that for the range of IMA from 0 to 45°, the self-vibration in *X* direction of the SFT structure will be from a small amplitude less than the wave frequency jumping to a large amplitude more than wave frequency. When IMA is around 5°, the self-vibration in *X* direction of the SFT structure is close to the wave frequency, thus the movement of the SFT structure will be substantial and will induce tether slack at a small wave height. Therefore in the SFT design, the BWR and IMA combination states that may induce slack process, should be avoid such that to prevent snap force in the tethers from happening.

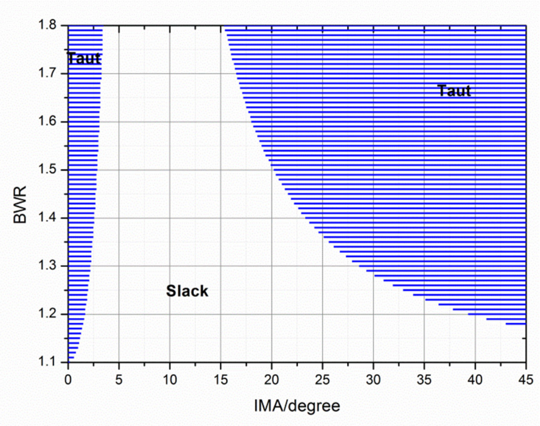

Fig. 7. STP based on critical wave height analysis (wave height: 12 m) [13].

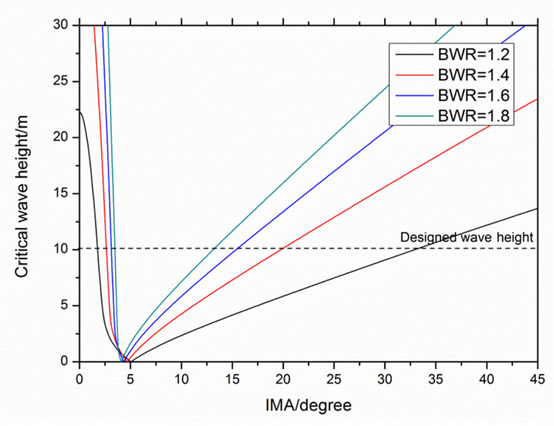

Fig. 8. Critical wave height versus IMA at different BWR [13].

4. Conclusions

The two issues of buoyancy-weight ratio (BWR) and slack-taut performance (STP) on the dynamic response and stability of SFT were comprehensively investigated in this paper and the conclusions are drawn as the follows.

(1) The variations of BWR and STP are very sensitive to the dynamic response of SFT. It is regarded that both BWR and STP are intrinsic issues in the domination of SFT stability due to the internal and external loadings.

(2) For BWR, the concept of "Synergetic range of BWR" is re-stated. This is defined as, for an SFT structure with related environmental conditions, a suitable range of BWR value exists, which will lead to less dynamic response and more stable for the SFT.

(3) For STP, the concept of "Slack-Taut Map" (STM) is confirmed and an STM is illustrated. The STM presents the coupling effect of BWR and STP on the dynamic response of SFT subjected to external cyclic loadings especially in certain severe cases. By the instruction of STM, a safe region of BWR and IMA will be identified, which will prevent the unexpected snap force from occurrence.

(4) The essential concepts of "Synergetic range of BWR" and "Slack-Taut Map" are the key points and very useful in the SFT analysis and design.

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