10

Experimental Investigation on Motions of Immersing Tunnel Element under Irregular Wave Actions

Zhijie Chen[1], Yongxue Wang[2], Weiguang Zuo[2],
Binxin Zheng[1] and Zhi Zeng[1], Jia He[1]
[1]Open Lab of Ocean & Coast Environmental Geology,
Third Institute of Oceanography, SOA
[2]State Key Laboratory of Coastal and Offshore Engineering,
Dalian University of Technology
China

1. Introduction

An immersed tunnel is a kind of underwater transporting passage crossing a river, a canal, a gulf or a strait. It is built by dredging a trench on the river or sea bottom, transporting prefabricated tunnel elements, immersing the elements one by one to the trench, connecting the elements, backfilling the trench and installing equipments inside it (Gursoy et al., 1993). Compared with a bridge, an immersed tunnel has advantages of being little influenced by big smog and typhoon, stable operation and strong resistance against earthquakes. Due to the special economical and technological advantages of the immersed tunnel, more and more underwater immersed tunnels are built or are being built in the world.

Building an undersea immersed tunnel is generally a super-large and challenging project that involves many key engineering techniques (Ingerslev, 2005; Zhao, 2007), such as transporting and immersing, underwater linking, waterproofing and protecting against earthquakes. Some researches with respect to transportation, *in situ* stability and seismic response of tunnel elements are seen to be carried out (Anastasopoulos et al., 2007; Aono et al., 2003; Ding et al., 2006; Hakkaart, 1996; Kasper et al., 2008). The immersion of tunnel elements was also studied (Zhan et al., 2001a, 2001b; Chen et al., 2009a, 2009b, 2009c).

The immersion of a large-scale tunnel element is one of the most important procedures in the immersed tunnel construction, and its techniques involve barges immersing, pontoons immersing, platform immersing and lift immersing (Chen, 2002). In the sea environment, the motion responses of a tunnel element in the immersion have direct influences on its underwater positioning operation and immersing stability. So a study on the dynamic characteristics of the tunnel element during its interaction with waves in the immersion is desirable. Although, some researches on the immersion of tunnel elements were done in the past years, there is still much work remaining to study further. Also, the study on the immersion of tunnel elements under irregular wave actions is not seen as yet.

The aim of the present study is to investigate experimentally the motion dynamics of the tunnel element in the immersion under irregular wave actions based on barges immersing

method. The motion responses of the tunnel element and the tensions acting on the controlling cables are tested.
The time series of the motion responses, i.e. sway, heave and roll of the tunnel element and the cable tensions are presented. The results of frequency spectra of tunnel element motion responses and cable tensions for irregular waves are given. The influences of the significant wave height and the peak frequency period of waves on the motions of the tunnel element and the cable tensions are analyzed. Finally, the relation between the tunnel element motions and the cable tensions is discussed.

2. Physical model test

2.1 Experimental installation and method

The experiments are carried out in a wave flume which is 50m long, 3.0m wide and 1.0m deep. The sketch of experimental setup is shown in Fig. 1. Assuming the movements of the barges on the water surface are small and can be ignored, the immersion of the tunnel element is directly done by the cables from the fixed trestle over the wave flume.
The immersed tunnel element considered in this study is 200cm long, 30cm wide and 20cm high, which is a hollow cuboid sealed at its two ends. The tunnel model is made of acrylic plate and concrete and the cables are modeled by springs and nylon strings that are made to lose their elasticity.

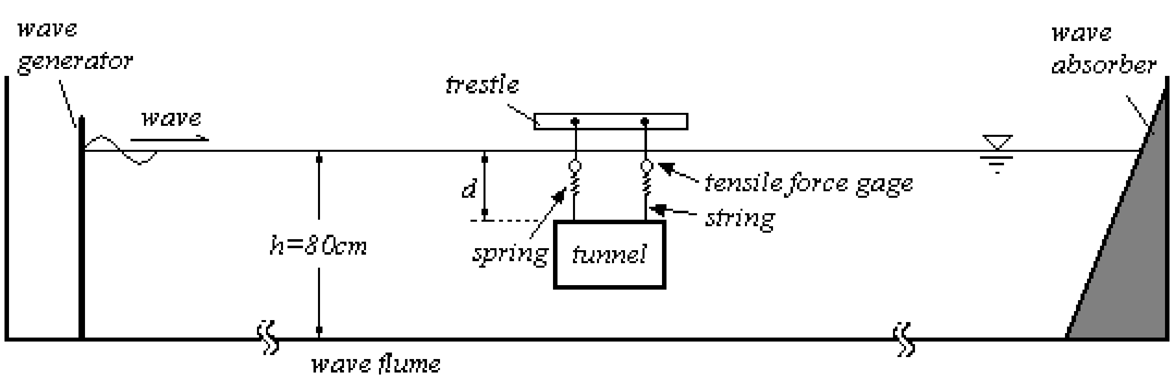


Fig. 1. Sketch of experimental setup

It is known that the immersion of the tunnel element in practical engineering is actually done by the ballast water, namely negative buoyancy, inside the tunnel element. The weight of the tunnel element model used in this experiment is measured as 1208.34N. When the model is completely submerged in the water, the buoyancy force acting on it is 1176.0N. So the negative buoyancy is equal to 32.34N, which is 2.75 percent of the buoyancy force of the tunnel element. The negative buoyancy makes the cables bear the initial tensions.
Water depth (h) in the wave flume is 80cm. The normal incident irregular waves are generated from the piston-type wave generator. The significant wave heights (H_s) are 3cm and 4cm, and the peak frequency period of waves (T_p) 0.85s, 1.1s and 1.4s, respectively. The experiments are conducted for the cases of three different immersing depths of the tunnel element, i.e., d=10cm, 30cm and 50cm, respectively. d is defined as the distance from the water surface to the top surface of the tunnel element.
Corresponding to the three immersing depths of the tunnel element, three kinds of springs with different elastic constants are used in the experiment. According to the properties of cables using in practical engineering and the suitable scale of the model test, the appropriate

springs are chosen. The relations between the elastic force and the spring extension are shown in Fig. 2. There are four strings that join four springs respectively to control the immersed tunnel element in the waves. Two strings are on the offshore side and the other two on the onshore side of the tunnel element. To measure the tensions acting on the strings, four tensile force gages are connected to the four strings respectively.

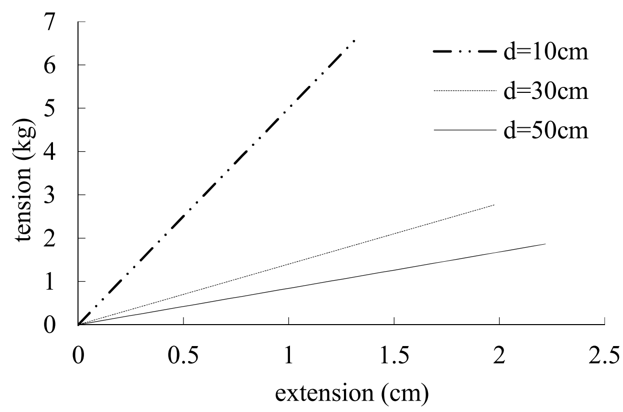


Fig. 2. Relations between the elastic force and the spring extension

The CCD (Charge Coupled Device) camera is utilized to record the motion displacements of the tunnel element during its interaction with waves. Two lights with a certain distance are installed at the front surface of the tunnel element, as shown in Fig. 3. When the tunnel element moves under irregular wave actions, the positions of the two lights are recorded by the CCD camera. Finally, the sway, heave and roll of the tunnel element are obtained from the CCD recorded images by the image analysing program.

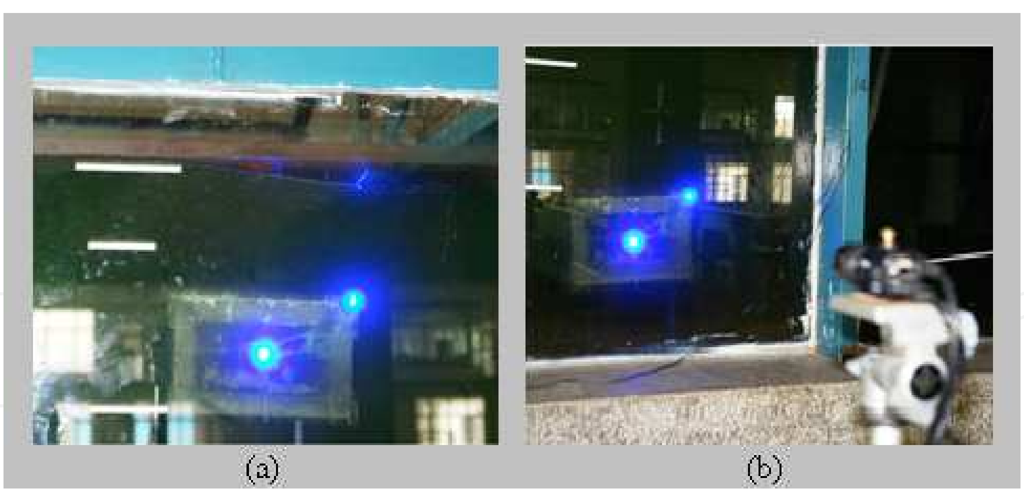
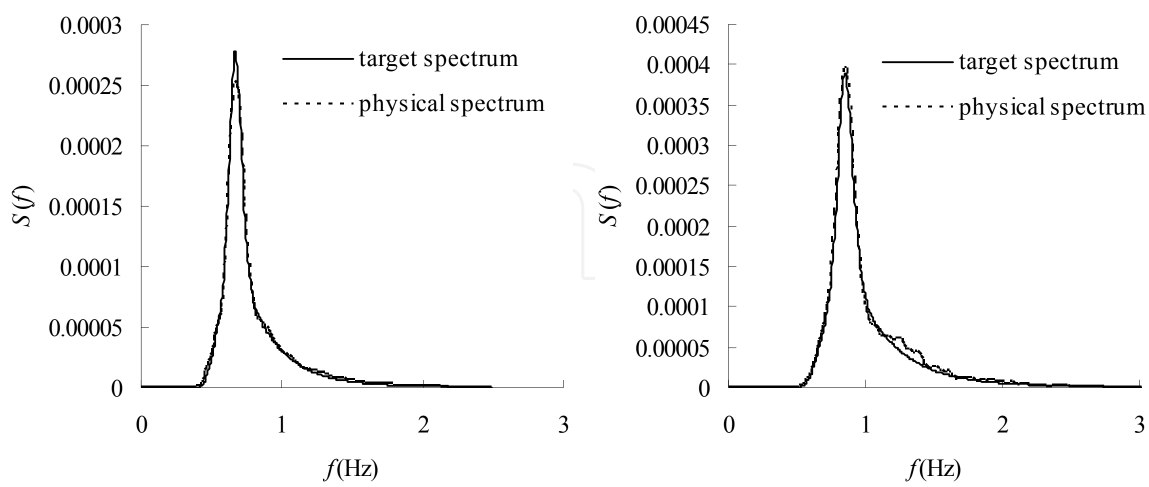


Fig. 3. Photo view of the tunnel element at the wave flume. (a) wave is propagating over the tunnel element; (b) the tunnel element and CCD

2.2 Simulation of wave spectra

In the experiment, Johnswap spectrum is chosen as the target spectrum to simulate the physical spectrum, and two significant wave heights, H_s=3.0cm and 4.0cm, and three peak frequency periods of waves, T_p=0.85s, 1.1s and 1.4s are considered. As examples, two groups of wave conditions, i.e. H_s=3.0cm, T_p=1.4s and H_s=4.0cm, T_p=1.1s, are taken to present the simulation of the physical wave spectra. Fig. 4 shows the results of the comparison between the target spectrum and physical spectrum. It is seen that they agree very well.



(a) H_s=3.0cm, T_p=1.4s (b) H_s=4.0cm, T_p=1.1s

Fig. 4. Measured and target spectrum

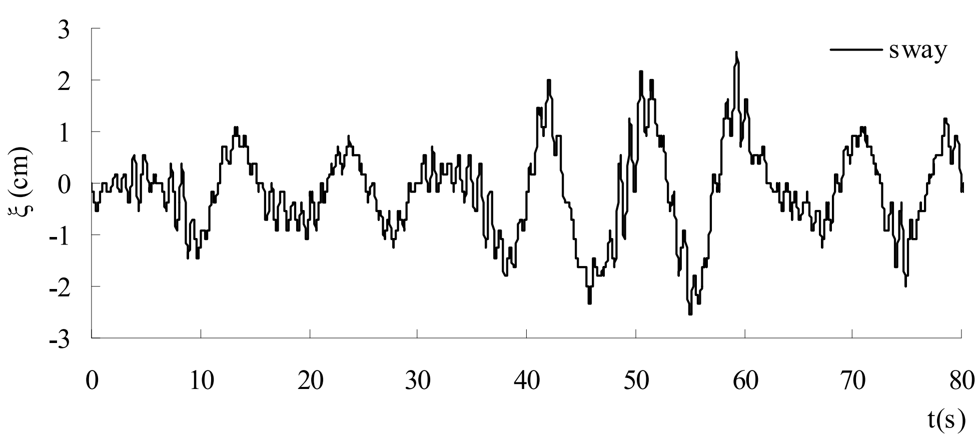
3. Experimental results and discussion

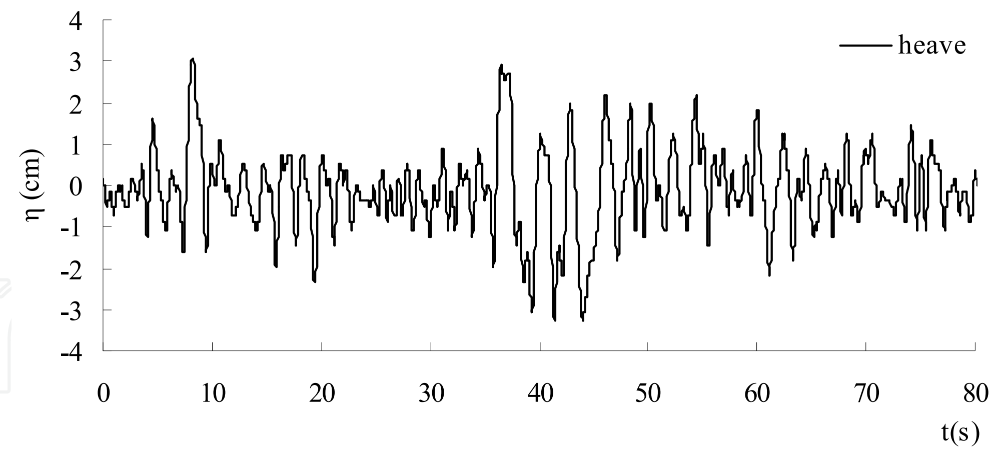
3.1 Motion responses of the tunnel element

The significant wave height and the peak frequency period of waves are the main influencing factors on the motion responses of the tunnel element under irregular wave actions. Moreover, in the different immersing depth positions, the motions of the tunnel element make differences. In this experiment, the different immersing depths, significant wave heights and peak frequency periods are considered to explore their impacts on the motions of the tunnel element.

3.1.1 Time series of the tunnel element motion responses

As an example, the time series of the tunnel element motion responses in the wave conditions H_s=3.0cm, T_p=0.85s and d=10cm within the time 80s are shown in Fig. 5. Under the normal incident wave actions, the tunnel element makes two-dimensional motions, i.e. sway, heave and roll.





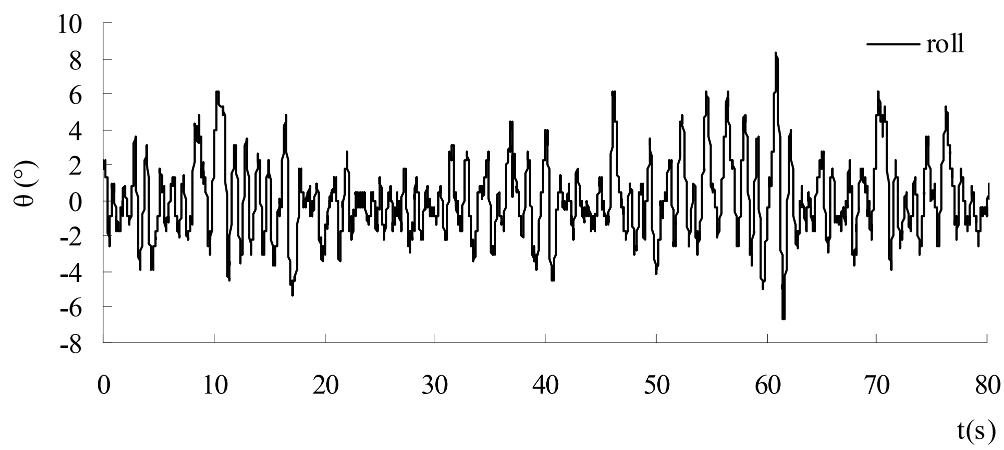
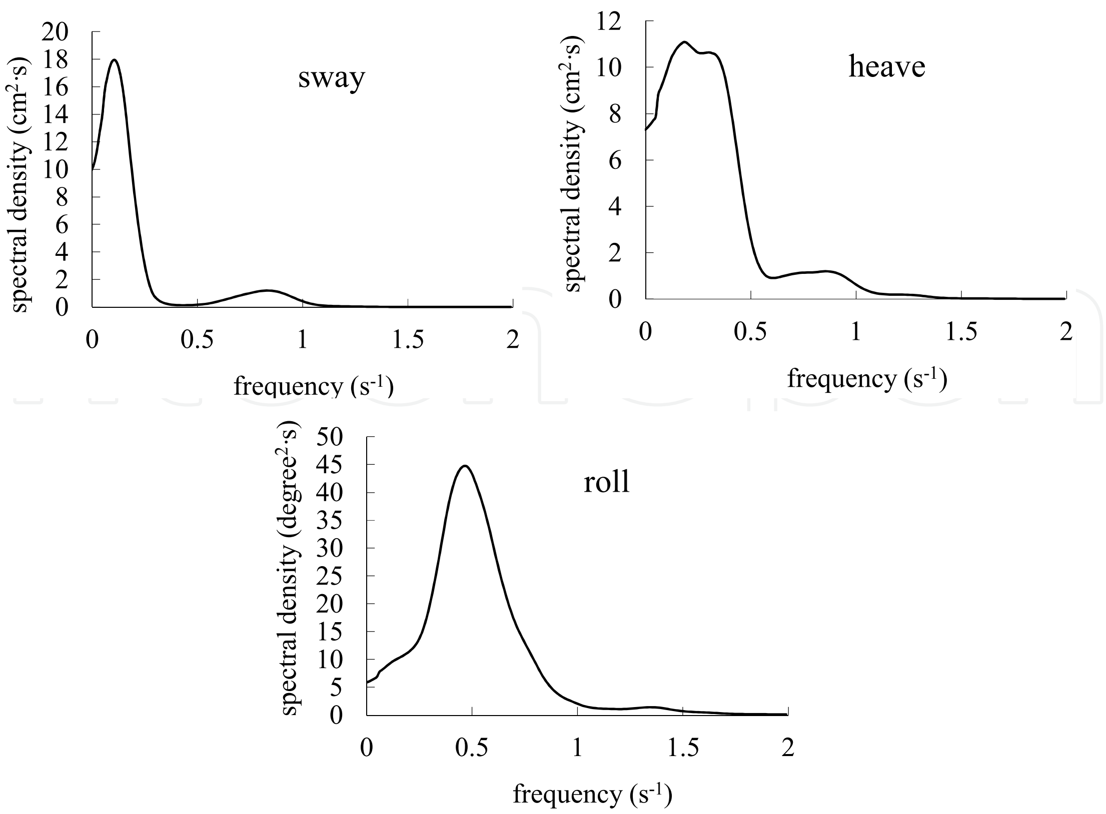


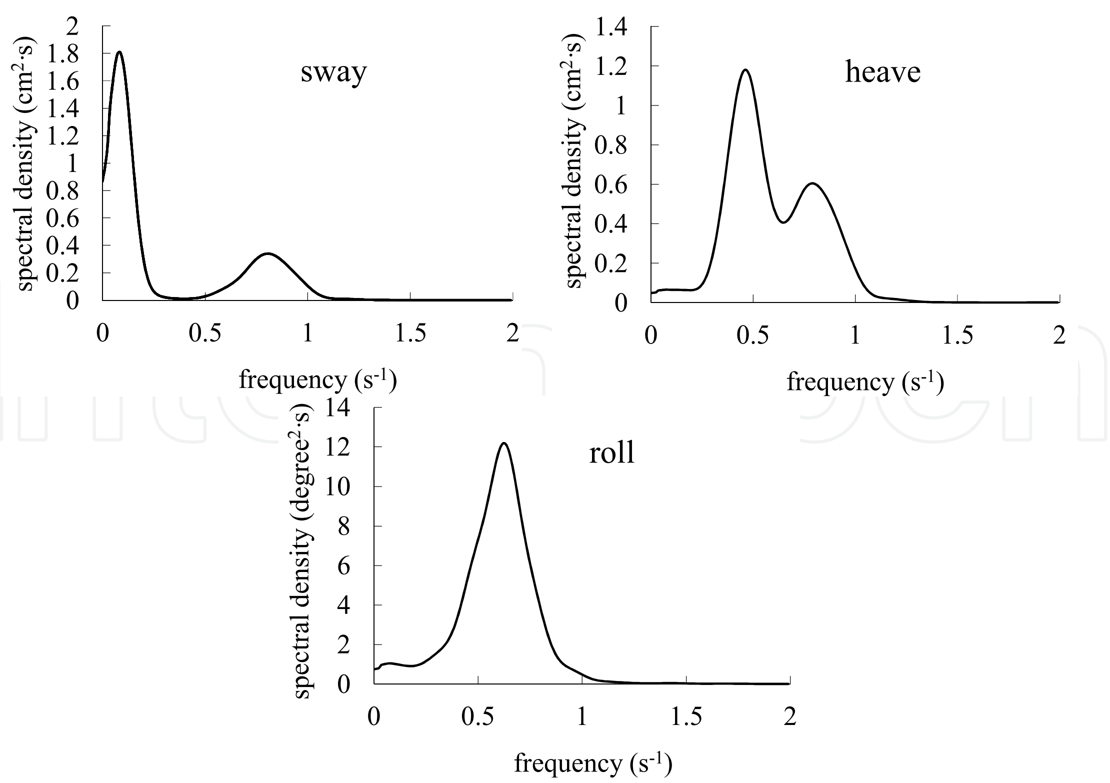
Fig. 5. Time series of the tunnel element motion responses (d=10cm, H_s=3.0cm, T_p=0.85s)

3.1.2 Motion responses of the tunnel element in the different immersing depth

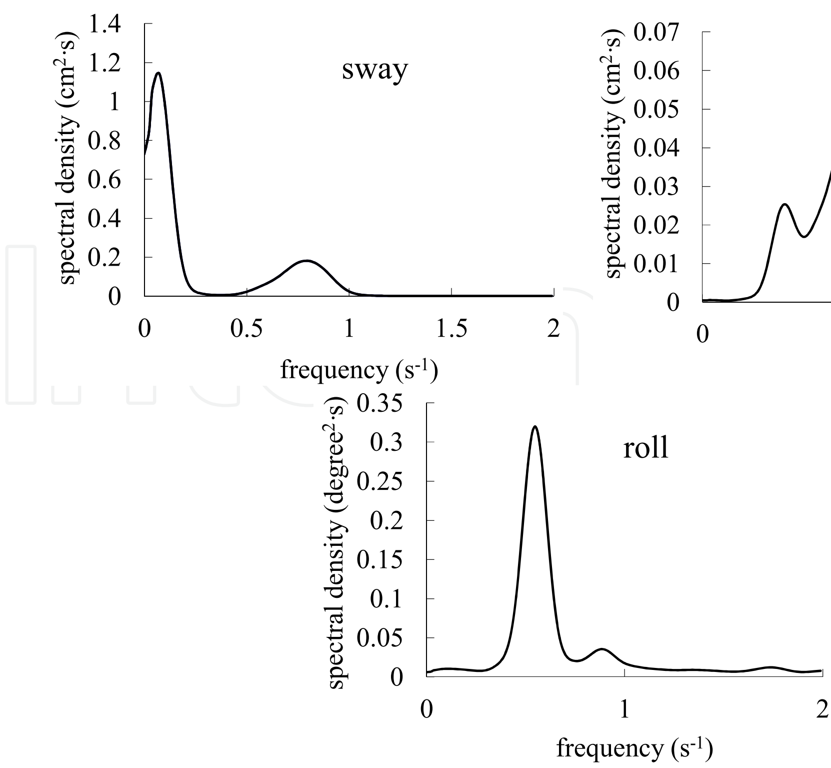
Fig. 6 gives the results of the frequency spectra of the tunnel element motion responses in the wave conditions H_s=4.0cm and T_p=1.1s for different immersing depths of the tunnel element. From the peak values of the frequency spectra curves, it is obvious that the motion responses of the tunnel element are comparatively large for the comparatively small immersing depth. Comparing the motions of the tunnel element of sway, heave and roll, the area under the heave motion response spectrum is larger than that under the sway motion response spectrum when the immersing depths are 10cm and 30cm, as indicates that the motion of the tunnel element in the vertical direction is predominant. In addition, it can be observed that there are two peaks on the curves of the sway and heave motion responses spectra. This illuminates that the low-frequency motions occur in the tunnel element besides the wave-frequency motions. The low-frequency motions are caused by the actions of cables. For the sway, the low-frequency motion is dominant, while the wave-frequency motion is relatively small. From the figure, it can be seen that the low-frequency motion is always larger than the wave-frequency motion for the sway as the tunnel element is in the different immersing depths. It reveals that the low-frequency motion is the main of the tunnel element movement in the horizontal direction. This can also be obviously observed from the curve of time series of the sway in Fig. 5. However, for the heave, as the immersing depth increases, the motion turns gradually from that the low-frequency motion is dominant into that the wave-frequency motion is dominant.



a. *d*=10cm



b. *d*=30cm

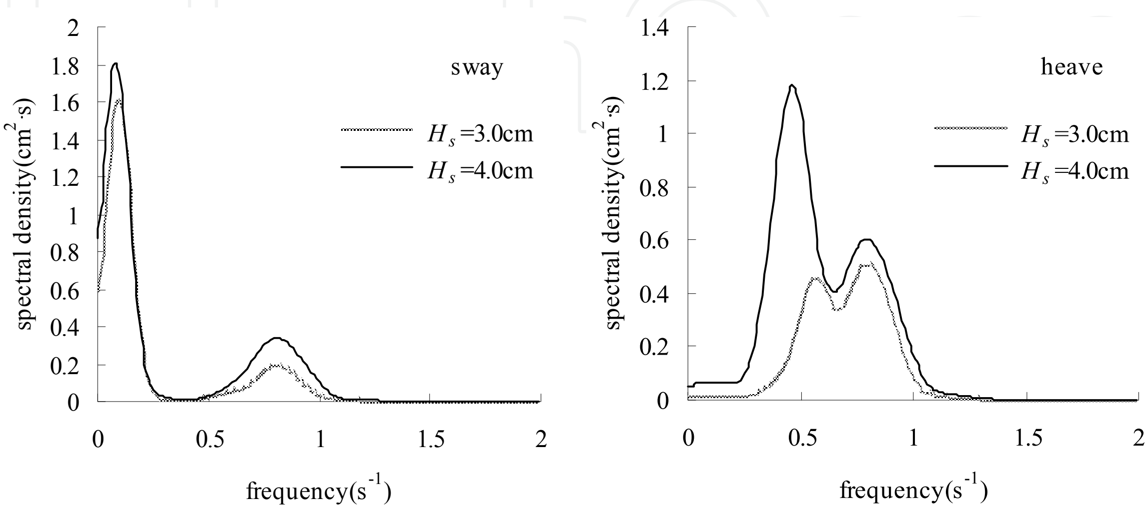


c. *d*=50cm

Fig. 6. Frequency spectra of the tunnel element motion responses for different immersing depths (H_s=4.0cm, T_p=1.1s)

3.1.3 Influence of the significant wave height on the tunnel element motions

The results of the frequency spectra of the tunnel element motion responses for different significant wave heights in the test conditions *d*=30cm and T_p=1.1s are shown in Fig. 7. From the figure, it is seen that the shapes of the frequency spectrum curves of the tunnel element motion responses are very similar for different significant wave heights, while just the peak values are different. Corresponding to the large significant wave height, the peak value is large, as well large is the area under the motion response spectrum. Apparently, the motion responses of the tunnel element are correspondingly large for the large significant wave height.



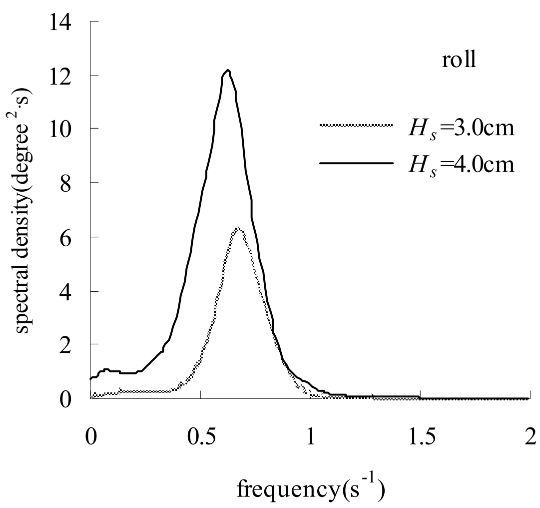
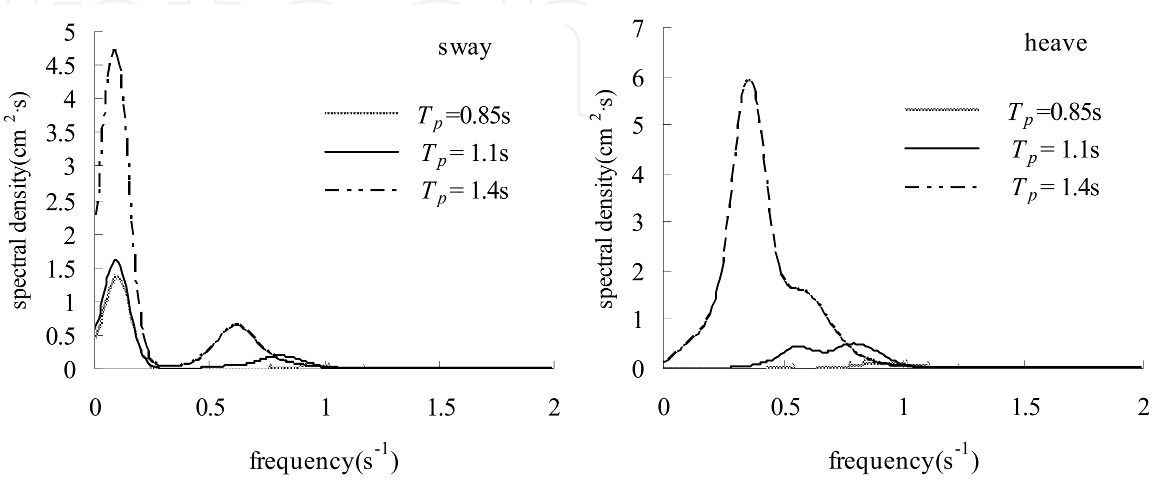


Fig. 7. Frequency spectra of the tunnel element motion responses for different significant wave heights (d=30cm, T_p=1.1s)

3.1.4 Influence of the peak frequency period on the tunnel element motions

Fig. 8 shows the results of the frequency spectra of the tunnel element motion responses in the test conditions d=30cm and H_s=3.0cm for different peak frequency periods of waves. It can be seen that the peak frequency period has an important influence on the motion responses of the tunnel element. The peak values of the frequency spectra of the motion responses increase markedly with the increase of the peak frequency period. Thus, the larger is the peak frequency period of waves, the larger are the motion responses of the tunnel element.



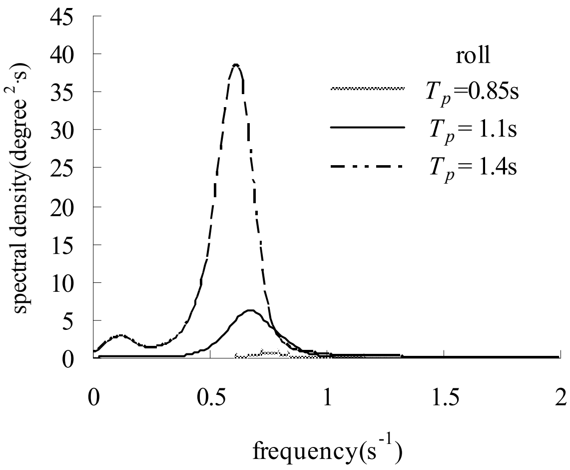


Fig. 8. Frequency spectra of the tunnel element motion responses for different peak frequency periods of waves (d=30cm, H_s=3.0cm)

Furthermore, in the figure it is shown that the frequency spectra of the tunnel element motion responses all have a peak at the frequency corresponding to the respective peak frequency period of waves, besides a peak corresponding to the low-frequency motion of the tunnel element. For the sway, the peak frequency corresponding to the low-frequency motion of the tunnel element is the same in the cases of different peak frequency periods. However, for the heave, the peak frequency corresponding to the tunnel element low-frequency motion varies with the peak frequency period. It increases as the peak frequency period increases. The reason may be that there occurs slack state in the cables during the movement of the tunnel element when the peak frequency period increases, for which there is no more the restraint from the motion of the tunnel element in the vertical direction from the cables at this time.

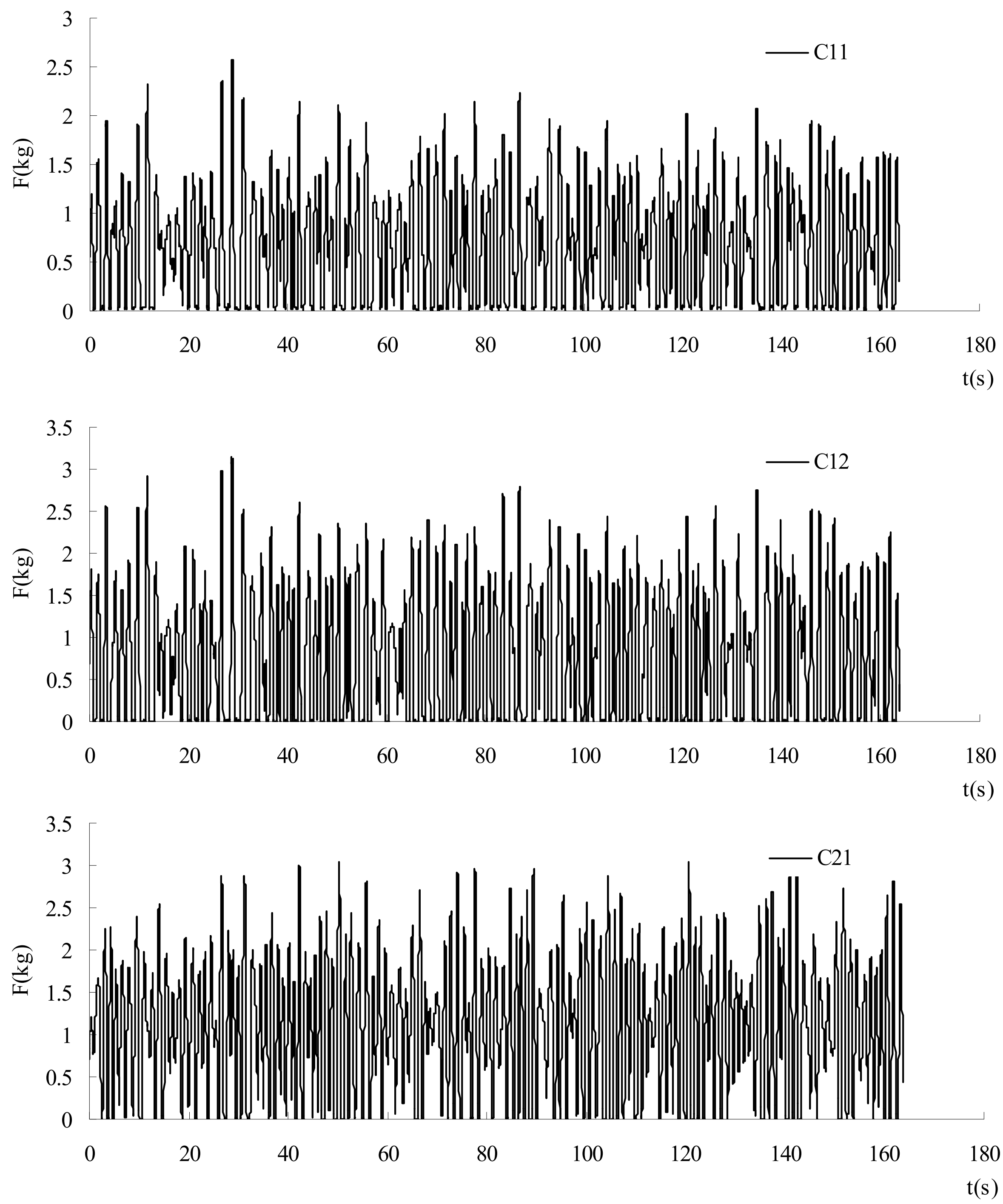
3.2 Cable tensions

3.2.1 Time series of cable tensions

As a typical case, Fig. 9 shows the time series of the cable tensions in the wave conditions H_s=4.0cm, T_p=1.1s and d=30cm within the time 160s. In the figure, $C11$ represents the front cable at the onshore side, $C12$ the back cable at the onshore side, $C21$ the front cable at the offshore side and $C22$ the back cable at the offshore side. It can be seen that the time series of tensions of the cables $C11$ and $C12$ at the onshore side are very similar, as well similar are those of the cables $C21$ and $C22$ at the offshore side. It shows that under the normal incident irregular wave actions the tunnel element does only two-dimensional motions. This can also be observed in the experiment from the movement of the tunnel element.

3.2.2 Cable tensions for the different immersing depth of the tunnel element

Fig. 10 shows the results of the frequency spectra of the cable tensions in the wave conditions H_s=4.0cm and T_p=1.1s for different immersing depths of the tunnel element. From the peak values of the frequency spectra curves and the areas under the frequency spectra, it is seen that the tensions acting on the cables are comparatively large in the case of comparatively small immersing depth, as is corresponding to the motion responses of the tunnel element. Furthermore, the peak values and the areas of the frequency spectra of the cable tensions at the offshore side are all larger than those of the cable tensions at the onshore side for different immersing depths. It indicates that the total force of the cables at the offshore side is larger than that of the cables at the onshore side. It is also shown that in the figure there are at least two peaks in the curves of the frequency spectra of the cable tensions, which are respectively corresponding to the wave-frequency motions and low-frequency motions of the tunnel element. When the tunnel element is at the position of a relatively small immersing depth, the frequency spectra of the cable tensions have other small peaks besides the two peaks at the wave frequency and the low frequency. It illustrates that the case of the forces generating in the cables is more complicated for the comparatively strong motion responses of the tunnel element under the wave actions when the immersing depth is relatively small.



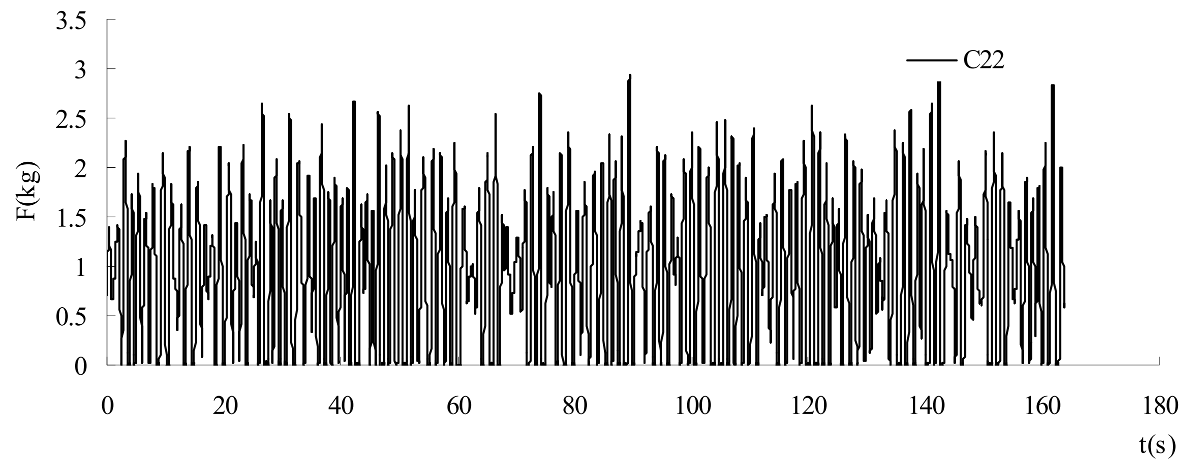
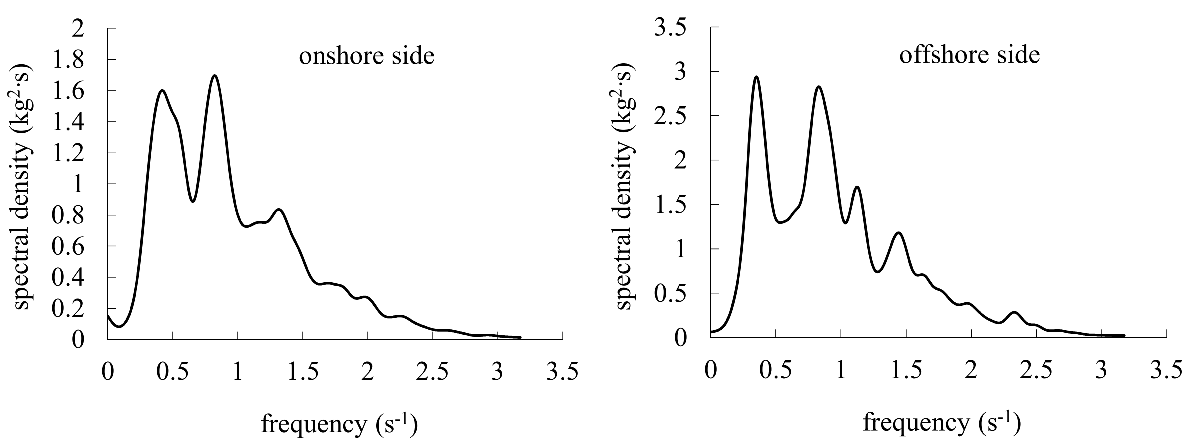
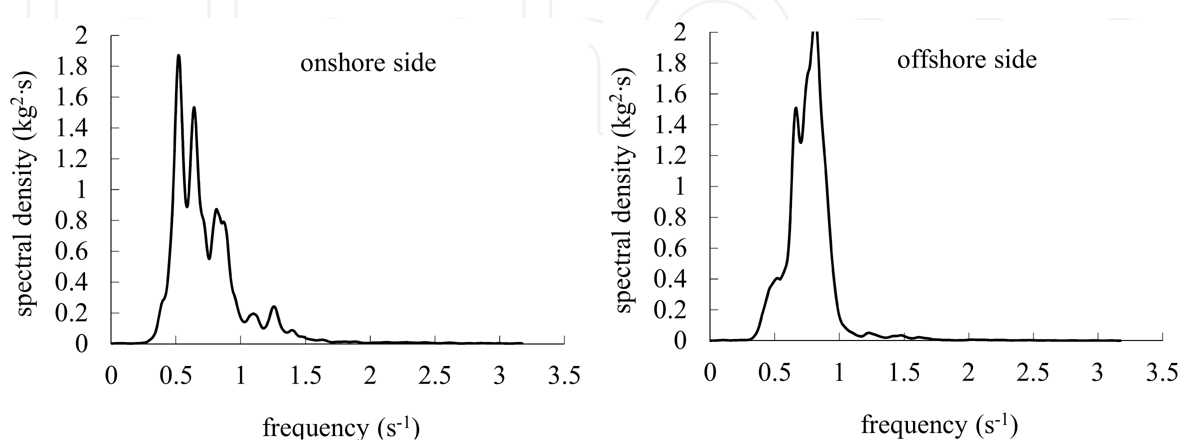


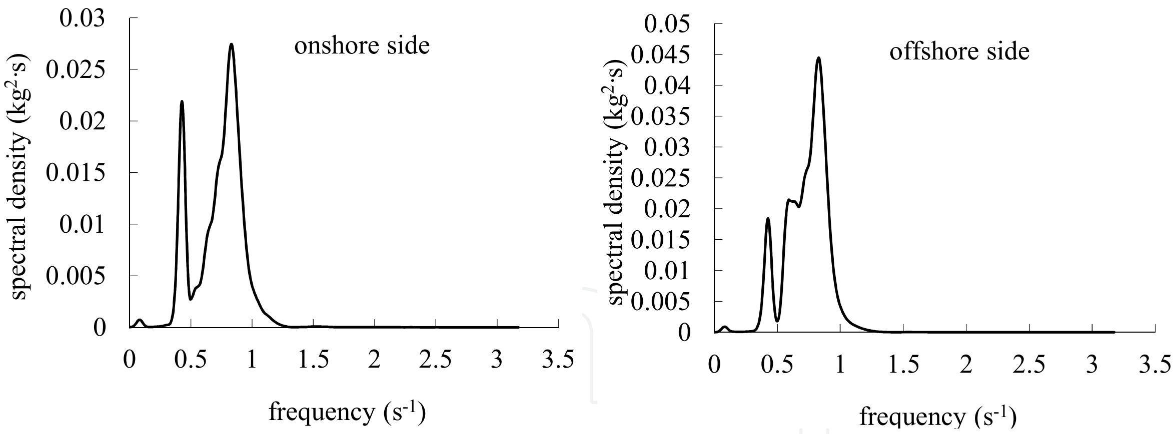
Fig. 9. Time series of tensions acting on the cables (d=30cm, H_s=4.0cm, T_p=1.1s, $C$11: front cable at the onshore side, $C$12: back cable at the onshore side, $C$21: front cable at the offshore side, $C$22: back cable at the offshore side)



a. d=10cm



b. d=30cm



c. d=50cm

Fig. 10. Frequency spectra of the cable tensions for different immersing depths (H_s=4.0cm, T_p=1.1s)

3.2.3 Influence of the significant wave height on the cable tensions

Fig. 11 gives the results of the frequency spectra of the cable tensions for different significant wave heights in the test conditions d=30cm and T_p=1.1s. It is shown that the area under the frequency spectrum of the cable tensions for the significant wave height H_s=4.0cm is larger than that for H_s=3.0cm. Therefore, the larger is the significant wave height, the larger are the cable tensions accordingly. This is corresponding to the case that the motion responses of the tunnel element are larger for the larger significant wave height. When the significant wave height increases, the wave effects on the tunnel element increase. Accordingly, the forces acting on the cables also become larger.

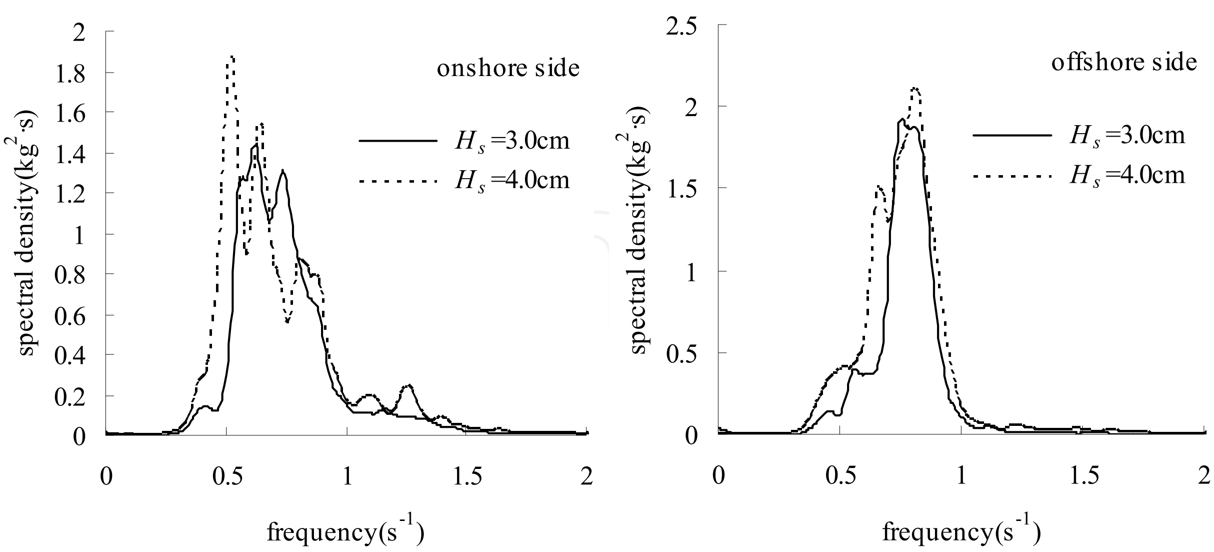


Fig. 11. Frequency spectra of the cable tensions for different significant wave heights (d=30cm, T_p=1.1s)

3.2.4 Influence of the peak frequency period on the cable tensions

The results of the frequency spectra of the cable tensions for different peak frequency periods of waves in the test conditions d=30cm and H_s=3.0cm are shown in Fig. 12. It is seen that the cable tensions are largely influenced by the peak frequency period. The peak values of the frequency spectra of the cable tensions increase rapidly as the peak frequency period increases. Corresponding to the case of the motion responses of the tunnel element for different peak frequency periods, the larger is the peak frequency period, the larger are also the cable tensions. For different peak frequency periods, the frequency spectra of the cable tensions all have a peak at the corresponding frequency. Besides, from the figure, it can be observed that the peaks of the frequency spectra at the lower frequency are obvious when the peak frequency period T_p=1.4s. This reflects that the low-frequency motions of the tunnel element become large with the increase of the peak frequency period of waves.

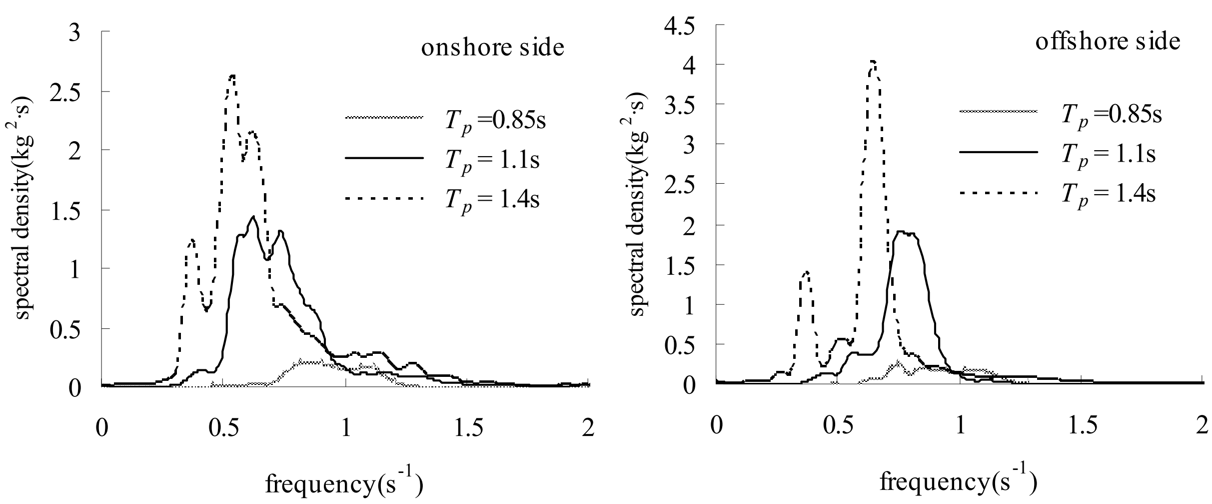


Fig. 12. Frequency spectra of the cable tensions for different peak frequency periods of waves (d=30cm, H_s=3.0cm)

3.3 Relation between the tunnel element motions and the cable tensions

The tunnel element moves under the irregular wave actions, and at the same time, the tunnel element is restrained by the cables in the motions. So the wave forces and cable tensions together result in the total effect of the motions of the tunnel element. On the other hand, the restraint of the cables from the movement of the tunnel element makes the cables bear forces. Hence, the motions of the tunnel element and the cable tensions are coupled. According to the discussion in the above context, in the case when the immersing depth is small and the significant wave height and the peak frequency period are large comparatively, the motion responses of the tunnel element are relatively large. And in the case of that, the variations of the cable tensions are accordingly more complicated.

Moreover, corresponding to the wave-frequency peak and low-frequency peak of the frequency spectra of the cable tensions, there occur the wave-frequency motions and low-frequency motions in the tunnel element. This also reflects directly the interrelation of the tunnel element motions and the cable tensions.

4. Conclusions

The motion dynamic characteristics of the tunnel element and the tensions acting on the controlling cables in the immersion of the tunnel element under irregular wave actions are experimentally investigated in this chapter. The irregular waves are considered normal incident and the influences of the immersing depth of the tunnel element, the significant wave height and the peak frequency period of waves on the tunnel element motions and the cable tensions are analyzed. Some conclusions are drawn as follows.

As the immersing depth is comparatively small, the motion responses of the tunnel element are relatively large. Besides the wave-frequency motions, the tunnel element has also the low-frequency motions that result from the actions of cables. For the sway of the tunnel element, for different immersing depth the low-frequency motion is always larger than the wave-frequency motion. While for the heave, with the increase of the immersing depth, the motion turns gradually from that the low-frequency motion is dominant into that the wave-frequency motion is dominant.

For the large significant wave height, the motion responses of the tunnel element are accordingly large. The peak values of the frequency spectra of the motion responses increase rapidly with the increase of the peak frequency period of waves. Especially, for the heave motion of the tunnel element, the peak frequency of the response spectrum corresponding to the low-frequency motion increases with the increasing peak frequency period.

The total force of the cables at the offshore side is larger than that of the cables at the onshore side of the tunnel element. Corresponding to the motion responses of the tunnel element, the cable tensions are relatively large and their variations are more complicated in the case as the immersing depth is small and the significant wave height and the peak frequency period are large comparatively. The changing laws of the tunnel element motions and the cable tensions reflect the interrelation of them.

In this chapter, the immersion of the tunnel element is done from the fixed trestle in the experiment, by ignoring the movements of the barges on the water surface. Actually, when the movements of the barges are relatively large, they have influences on the motions of the tunnel element. The influences of the movements of the barges on the tunnel element motions will be considered in the further researches. The numerical investigation will also be carried out on the motion dynamics of the tunnel element in the immersion under irregular wave actions.

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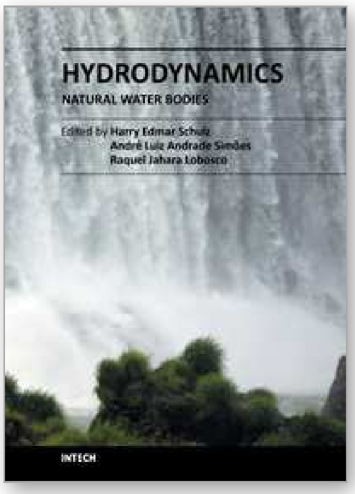

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The knowledge of the characteristics of the fluids and their ability to transport substances and physical properties is relevant for us. However, the quantification of the movements of fluids is a complex task, and when considering natural flows, occurring in large scales (rivers, lakes, oceans), this complexity is evidenced. This book presents conclusions about different aspects of flows in natural water bodies, such as the evolution of plumes, the transport of sediments, air-water mixtures, among others. It contains thirteen chapters, organized in four sections: Tidal and Wave Dynamics: Rivers, Lakes and Reservoirs, Tidal and Wave Dynamics: Seas and Oceans, Tidal and Wave Dynamics: Estuaries and Bays, and Multiphase Phenomena: Air-Water Flows and Sediments. The chapters present conceptual arguments, experimental and numerical results, showing practical applications of the methods and tools of Hydrodynamics.