Research on the Influence of Seismic Traveling Wave Effect on Long-span Double-layer Cylindrical Reticulated Shell Structure

Weidong Xie[1], Xiaojun Hu[1], Xiangsheng Tao[2,*], Zhihao Su[2], Guangjie Zhang[1]

[1]CCCC Second Harbor Consultants Co., Ltd., Wuhan 430060, China
[2]School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

*Corresponding authors'e-mail:1328109915@qq.com

Abstract. Based on the requirement of coal production capacity development in China, the design of dry coal sheds for storage is developing towards long spans and increased spatial capacity. The long-span double-layer cylindrical reticulated shell structure has emerged as the most widely adopted structural form for dry coal sheds. However, for structures with spans exceeding 120 m, the influence of the traveling wave effect on the structure cannot be disregarded. This paper focuses on a coal shed with a long-span double-layer cylindrical reticulated shell structure and utilizes the time history analysis method under multi-dimensional and multi-point excitation and Midas Gen software to study the influence factors of seismic traveling wave effect on the structure. The results reveal that: (1) A greater apparent seismic wave velocity contributes to a smaller impact of traveling wave effect on the long-span double-layer cylindrical reticulated shell structure; (2) Attention should be particularly focused on this impact when seismic waves propagate along the longitudinal span of the structure at a slow pace; (3) The traveling wave effect of near seismic waves on long-span double-layer cylindrical reticulated shell structure is greater than that of far seismic waves.

Keywords: Long-span double-layer cylindrical reticulated shell structure; traveling wave effect; multi-point excitation; apparent seismic wave velocity; hypocenter direction; epicentral distance.

1 Introduction

The earthquake is a geological disaster, making the prevention of earthquake disasters a focus of current research [1]. For long-span spatial structures, the spatial distribution of bearings results in a time difference when seismic waves reach different bearings during an earthquake, and this spatial variation characteristic is known as the traveling wave effect. Dry coal sheds exhibit various structural forms, such as truss structures, rigid frame structures, and cylindrical reticulated shell structures, among which the cylindrical reticulated shell structure wins the most widespread application with its mature technology and obvious advantages [2]. Numerous studies have found that the influence

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of seismic traveling wave effect on long-span structures is related to the structure and seismic wave characteristics. At present, the seismic analysis methods mainly include the response spectrum method, random vibration method, and time history analysis method [3]. The spatial variation characteristics of earthquakes should be considered in terms of long-span structures [4], with particular attention to the traveling wave effect [5, 6]. Many domestic and international scholars have studied the influence of the traveling wave effect on long-span structures.

Chu and Ye [7] took the long-span grid structure as the research object, considered the spatial variation characteristics of ground motion, and concluded that there are more plastic members and their distribution is more uniform in the structural response considering multi-point excitation.

Di and Lou [8] examined the partial coherence effect and traveling wave effect of synthetic seismic waves and calculated the multi-dimensional and multi-point input dynamic response of the single-layer cylindrical reticulated shell structure. Compared with the consistent input calculation results, the difference between the two results is closely related to the natural vibration frequency and ground motion frequency of the structure.

Taking the Tianjin Olympic Center as an example, Ramadan. [9] studied the influence of the traveling wave effect on long-span grid structures and concluded the necessity of multi-dimensional and multi-point seismic input for long-span grid structures. If the non-stationary seismic response is excluded, the seismic design of the structure tends to be conservative.

Harichandran. [10] investigated the traveling wave effect of long-span bridge structures under random earthquakes and demonstrated that the traveling wave effect is related to the structure and the ground motion characteristics.

Multiple scholars have compared and analyzed the seismic traveling wave effect according to different structure types and parameters. There are many factors affecting ground motion characteristics, including hypocenter, propagation path, epicentral distance, and site conditions. Studying the traveling wave effect involves considering how ground motion characteristics influence it, necessitating further exploration of its impact on specific structures. Therefore, this paper takes a coal shed with a long-span double-layer cylindrical reticulated shell structure as the research object and focuses on the influence of the traveling wave effect on this structure with different ground motion characteristics.

2 Research content

Building upon prior research and identifying existing challenges, this paper leverages real-world engineering projects, with a coal shed with a large-span double-layer cylindrical reticulated shell structure as the research object. It simulates the traveling wave effect through the principle of multi-dimensional and multi-point excitation, which involves determining the time difference of seismic waves reaching different bearings based on the waves' propagation speed and the spacing of bearings, and applying distinct seismic waves to each bearing. Additionally, according to the ground motion characteristics, the influence law of the traveling wave effect on the long-span double-layer cylindrical reticulated shell structure is studied from the aspects of the apparent seismic wave velocity, hypocenter direction, and epicentral distance. The main research content is as follows. Based on the actual project, the dynamic time history analysis for the long-span double-layer cylindrical reticulated shell model is carried out by utilizing the multi-dimensional multi-point excitation principle and Midas Gen software. A comparative analysis of structural dynamic responses is performed between multi-dimensional multi-point excitation and consistent excitation. Based on the comparative results, the research explores the impact patterns of the traveling wave effect on the long-span double-layer cylindrical reticulated shell structure under different seismic characteristics, such as apparent seismic wave velocity, hypocenter direction, and epicentral distance, and proposes some recommendations for the shell design.

2.1 Project overview

This paper focuses on a coal shed with a long-span double-layer cylindrical reticulated shell structure in a wharf project of CCCC Second Harbor Consultants Co., Ltd., whose proposed site belongs to a Class III site, and the design earthquake group is the first group. The characteristic period of the ground motion response spectrum is 0.45 s, the seismic fortification intensity is 8 degrees, the basic earthquake acceleration of the design is 0.30 g, and the intended service life is 50 years.

The double-layer cylindrical reticulated shell structure has a span of 125 m, a height of 48.50 m, a rise-span ratio of 0.39, and a total length of 349.70 m. There are 86 trusses in the longitudinal direction of the double-layer cylindrical reticulated shell structure, with the spacing between the bearings at both longitudinal sides of 3.70 m, and the spacing between the other longitudinal bearings of 4.20 m. The axonometric drawing of the coal shed with the long-span double-layer cylindrical reticulated shell structure is shown in Figure 1.

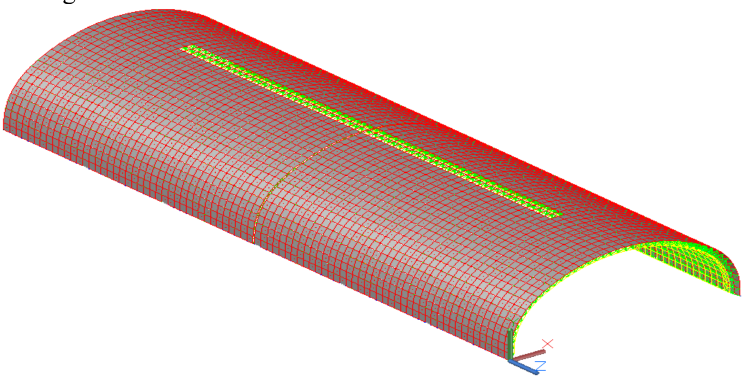


Fig. 1. Axonometric drawing of the coal shed with the long-span double-layer cylindrical reticulated shell structure

2.2 Seismic wave selection

Following the principle of seismic wave selection and considering that the proposed site of this coal shed is a Class III site, this paper chooses two classical natural seismic waves (El Centro wave and Taft wave) and one artificial wave (hereinafter referred to as three seismic waves). The artificial wave is synthesized through the fitting iterative method, where the initial phase of the artificial wave is set to the phase angle of the chosen natural seismic wave. Through iterative simulations with the fitting iterative method, the artificial wave was refined to closely match the standard response spectrum curve. This paper selects an artificial wave with a relatively high fitting degree. At the first three vibration mode periods of the structure, the maximum difference between the average seismic influence coefficient curves of the three seismic waves and the seismic influence coefficient curves used in the mode decomposition response spectrum method is 11%, with an average difference of 7%, all within 20%, as shown in Table 1. This meets the requirements of the code on statistical significance.

Table 1. Comparison between curves of the time history response spectrum and the standard response spectrum

Vibration mode	Vibration mode period	Time history average influence coefficient	Standard response spectrum influence coefficient	Time history average influence coefficient/standard response spectrum influence coefficient
1	2.07	0.35	0.38	0.92
2	1.01	0.78	0.77	1.01
3	0.87	0.99	0.89	1.11

3 Influencing factors of traveling wave effect

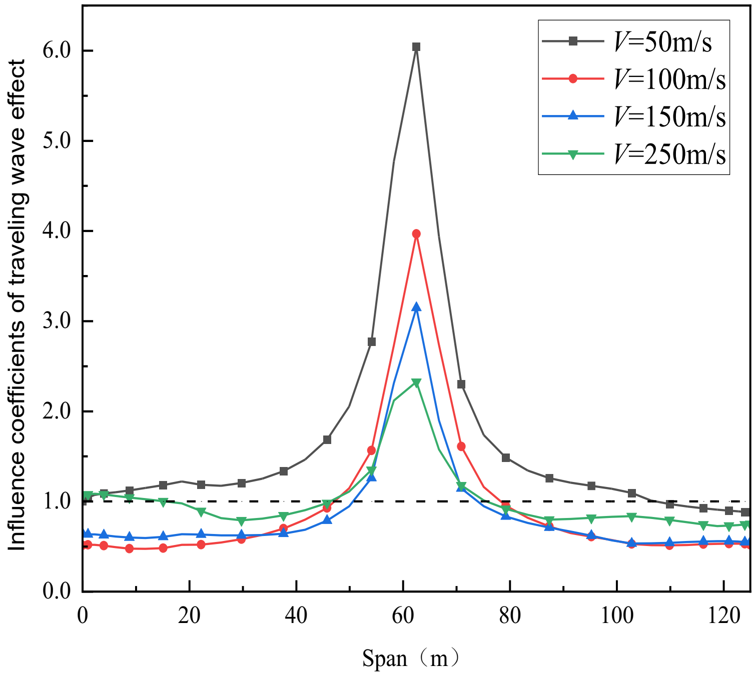
To describe the influence degree of traveling wave effect conveniently, the influence coefficient of traveling wave effect (α) is introduced, and the calculation formula is as follows.

$$\alpha = \frac{\text{Peak internal force in bars under multi-point excitation}}{\text{Peak internal force in bars under consistent excitation}} \tag{1}$$

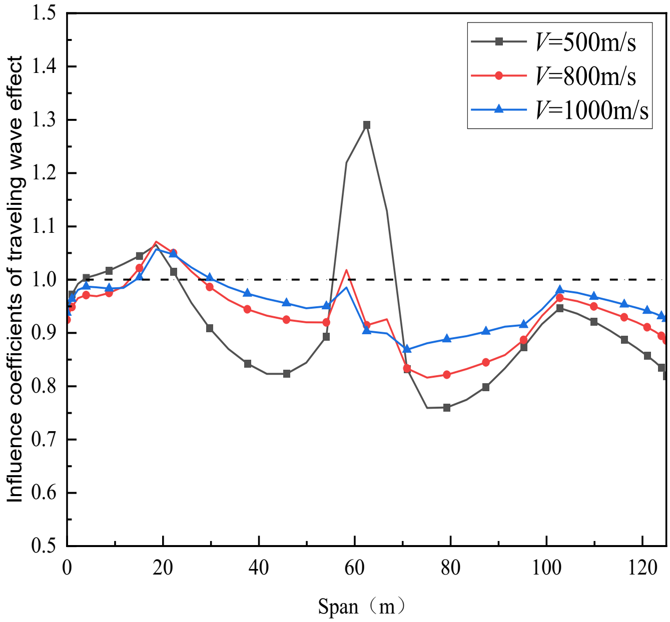
When $\alpha>1$, it shows that the peak internal force of the bar under multi-point excitation exceeds that under consistent excitation. This indicates an unfavorable influence of traveling wave effect on the bar, classifying it as an unfavorable bar for the whole structure. When $\alpha<1$, traveling wave effect is beneficial to the structure, and the bar can be regarded as a favorable component.

3.1 Influence of the apparent seismic wave velocity on the traveling wave effect

Apparent seismic wave velocity refers to the propagation velocity of seismic waves observed along the survey line on the ground surface. In this section, the El Centro wave, Taft wave, and artificial wave are used to calculate and analyze the multi-dimensional and multi-point excitation of the structure under different apparent wave velocities. Typical transverse bars of the coal shed with the long-span double-layer cylindrical reticulated shell structure are selected as the research object to study the influence of seismic traveling wave effect on the structure under different apparent wave velocities. According to the characteristics of rock's shear wave velocity or soil's equivalent shear wave velocity in the overlying soil layer within Class I_0~IV sites, the apparent seismic wave velocity of 50 m/s, 100 m/s, 150 m/s, 250 m/s, 500 m/s, 800 m/s, 1000m/s, and other values were selected. In specific calculations, earthquakes with different apparent wave velocities are realized by controlling the arrival times of seismic waves at different bearings. This paper analyzed and calculated the traveling wave effect of the engineering structure under different apparent wave velocities of the three seismic waves. The detailed results are illustrated in Figures 2~4.

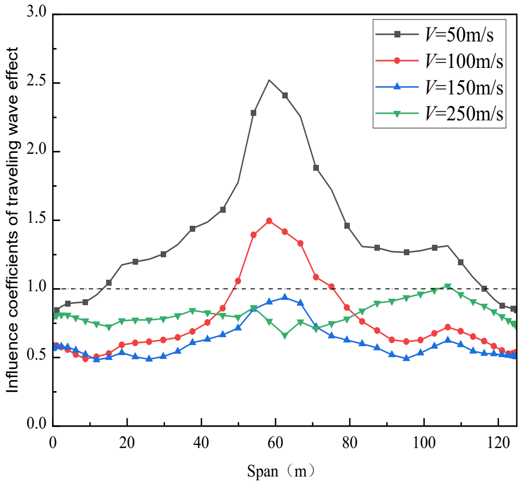


(a) Apparent wave velocity less than 500 m/s

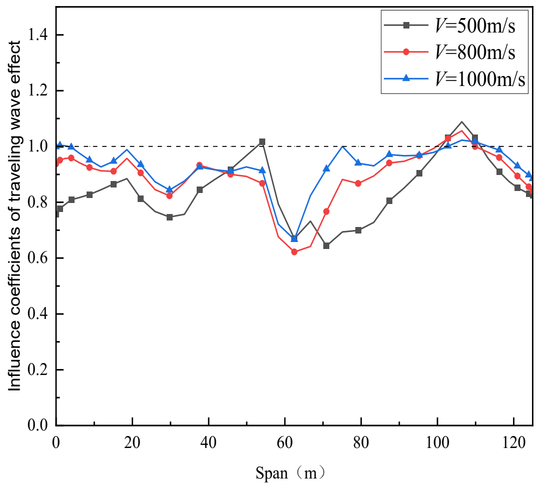


(b) Apparent wave velocity greater than 500 m/s

Fig. 2. Influence coefficients of traveling wave effect for the El Centro wave with different apparent wave velocities

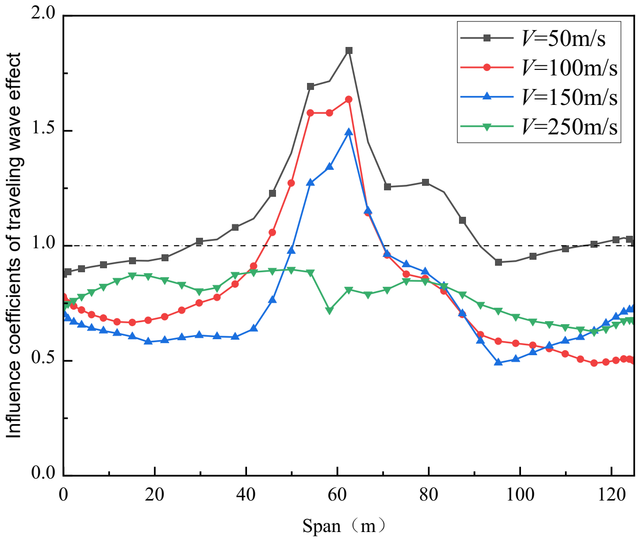


(a) Apparent wave velocity less than 500 m/s

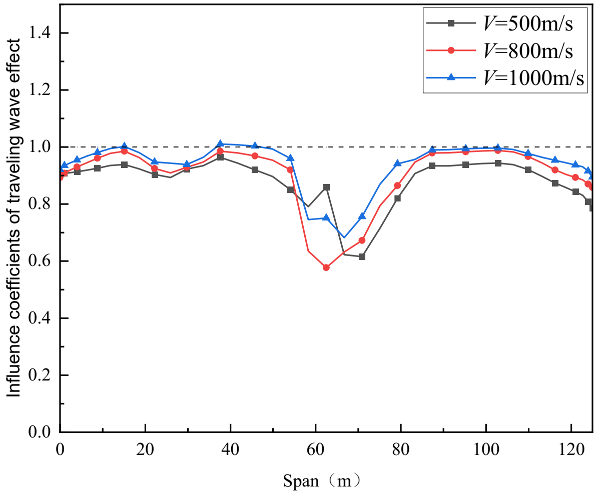


(b) Apparent wave velocity greater than 500 m/s

Fig. 3. Influence coefficients of traveling wave effect for the Taft wave with different apparent wave velocities



(a) Apparent wave velocity less than 500 m/s



(b) Apparent wave velocity greater than 500 m/s

Fig. 4. Influence coefficients of traveling wave effect for the artificial wave with different apparent wave velocities

Figures 2~4 demonstrate that for the unfavorable bars with α>1 near the mid-span, α radually decreases with the rise of the apparent wave velocity; for the favorable bars with α<1 on both sides, α gradually drops as the apparent wave velocity increases. Therefore, a greater apparent wave velocity leads to a smaller influence of the traveling wave effect on the long-span double-layer cylindrical reticulated shell structure. When the apparent wave velocity reaches 800 m/s, α tends to 1, and the influence of multi-point excitation on the structure closely aligns with that of consistent excitation.

To observe more intuitively how traveling wave effect of the three seismic waves influences the long-span double-layer cylindrical reticulated shell structure, the following two indexes are introduced:

(1) The percentage of bars with a traveling wave effect influence less than 10% indicates the proportion of bars with α between 0.9 and 1.1. A higher percentage indicates that more bars are affected by the traveling wave effect less than 10%, suggesting a smaller impact on the overall structure.

(2) The maximum value of α signifies the maximum influence of the traveling wave effect on structural bars, with a smaller value indicating a lesser impact on the structure.

With the change of apparent wave velocity, Figure 5 shows the percentage of bars with a traveling wave effect influence of less than 10%. As the apparent wave velocity increases, the percentage rises, while the influence of the traveling wave effect on the structure decreases. The maximum value of α varies with the apparent wave velocity, as illustrated in Figure 6. When the apparent wave velocity falls below 500 m/s, the maximum value of α decreases with the increase of the apparent wave velocity. When the apparent wave velocity reaches 800 m/s, the maximum value of α is stable around 1, which indicates that the traveling wave effect has little influence on this double-layer cylindrical reticulated shell structure.

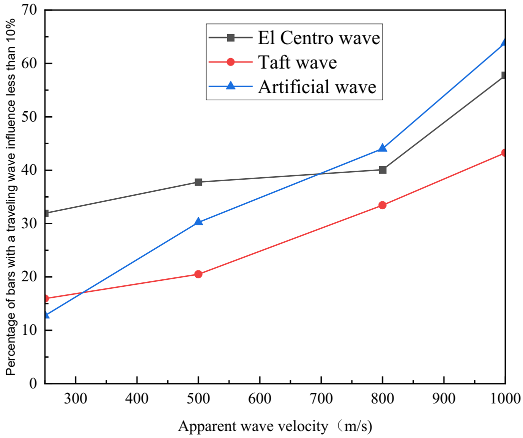


Fig. 5. Percentage of bars with a traveling wave effect influence less than 10%

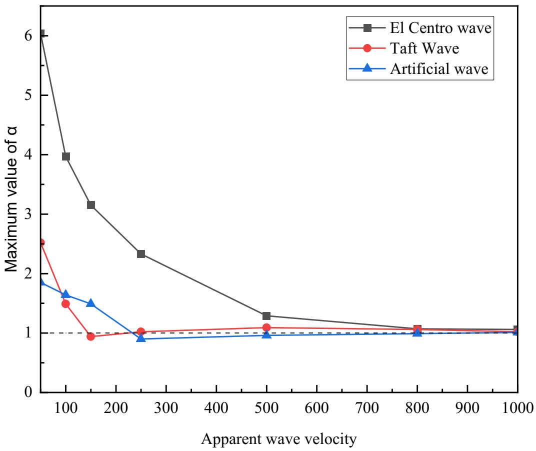


Fig. 6. Maximum value of the influence coefficient of traveling wave effect

Figures 5 and 6 show that while the traveling wave effect of the three seismic waves exhibits varying degrees of influence on the double-layer cylindrical reticulated shell structure (with the traveling wave effect of the El Centro wave having the greatest influence on the structure), the influence law of seismic wave traveling wave effect on the structure is consistent when the apparent wave velocity changes. This suggests a certain degree of generality in the conclusion: as the apparent wave velocity increases, the influence of the traveling wave effect on the large-span double-layer cylindrical reticulated shell structure decreases. When this velocity increases to a sufficiently high level, and the time difference of seismic waves reaching two bearings (Δt) is less than 0.15 s, the influence of the traveling wave effect on long-span double-layer cylindrical reticulated shell structure can be ignored.

3.2 Influence of the hypocenter direction on the traveling wave effect

In general calculation, seismic waves propagate along the span direction of the long-span double-layer cylindrical reticulated shell structure. However, in practical engineering, buildings may suffer from earthquakes from different directions. In order to examine the influence of the traveling wave effect of seismic waves in different hypocenter directions on the long-span double-layer cylindrical reticulated shell structure, this section performs multi-dimensional and multi-point excitation analysis on this structure under a three-dimensional earthquake. It selects the classical natural El Centro wave for analysis and the transverse upper chord in the middle of the reticulated shell structure as the research object. Moreover, during calculation, the peak acceleration of seismic waves in the X, Y, and Z directions is adjusted according to the ratio of 1:0.85:0.65.

During multi-point ground motion input, the presence of the changeable seismic wave propagation direction angle results in varying time differences of seismic waves reaching the bearings on both sides. Therefore, when changing the angle, it is necessary to calculate the time difference, as shown in Figure 7. With the apparent seismic wave velocity and structural span determined, this time difference differs for various hypocenter directions.

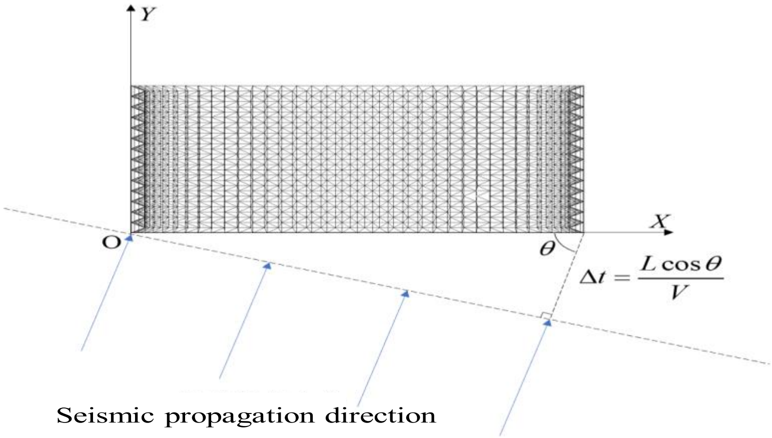
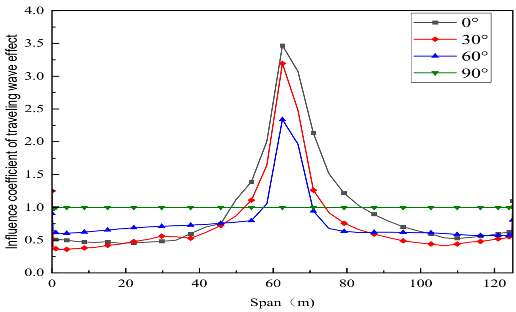
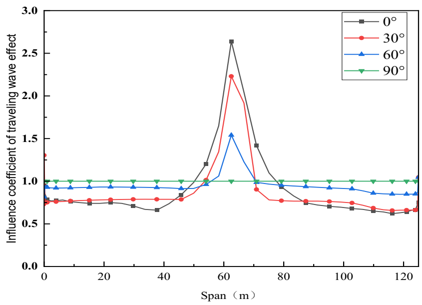


Fig. 7. Schematic diagram of the seismic propagation direction and time difference under multi-point excitation

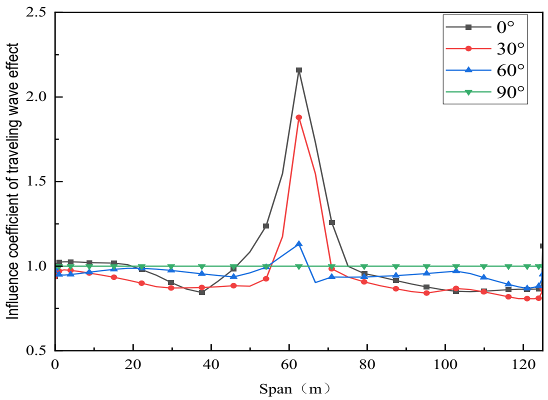
To avoid the contingency of analysis results and and account for potential site-specific conditions in actual projects, this section selects several groups of seismic waves under different sites for calculation. For Class I sites, the apparent seismic wave velocity is set at 500 m/s; For Class II sites, it is 300 m/s; For Class III sites, it is 200 m/s; for Class IV sites, it is 100 m/s. In this section, four groups of seismic waves with angles of 0°, 30°, 60°, and 90° between the propagation direction of seismic waves and the span direction of the structure are selected for calculation, and the calculation results under multi-dimensional and multi-point excitation are compared with those under consistent excitation. Thus, the influence coefficients of the seismic traveling wave effect in different hypocenter directions are obtained, as shown in Figure 8. The analysis reveals that under seismic waves with the above four apparent wave velocities, α approaches 1, and the influence coefficient of traveling wave effects of unfavorable bars diminishes while that of favorable bars increases with an increasing angle between the propagation direction and the span direction of the cylindrical reticulated shell structure. When the ground motion input angle is 90°, the seismic waves reach both sides of the bearings at the same time, which is equivalent to consistent excitation. Therefore, a larger angle between the seismic wave's propagation direction and the structure's span direction contributes to a smaller time difference of seismic waves reaching the bearings on both sides, yielding a more consistent result between multi-point and consistent excitation calculations, and reducing the impact of traveling wave effects on the structure.



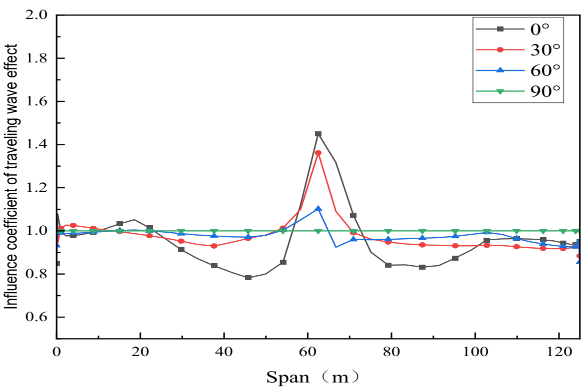
(a) Apparent wave velocity 100 m/s



(b)Apparent wave velocity 200 m/s



(c) Apparent wave velocity 300 m/s



(d) Apparent wave velocity 500 m/s

Fig. 8. Influence coefficient of traveling wave effect under different ground motion input angles

The maximum influence coefficient of the traveling wave effect can directly reflect the influence degree of the traveling wave effect on the structure. This maximum value under different apparent wave velocities and different ground motion input angles is shown in Figure 9. The results show that when the apparent seismic wave velocity is constant, a larger angle between the propagation direction of seismic waves and the span direction of the structure yields a smaller influence of the traveling wave effect on the structure. Meanwhile, a larger apparent wave velocity also results in a smaller influence, which is consistent with the conclusion obtained in Section 2.1. Therefore, when considering the seismic traveling wave effect for long-span double-layer cylindrical reticulated shell structures, we should focus on the slow seismic propagation along the long-span direction of the structure.

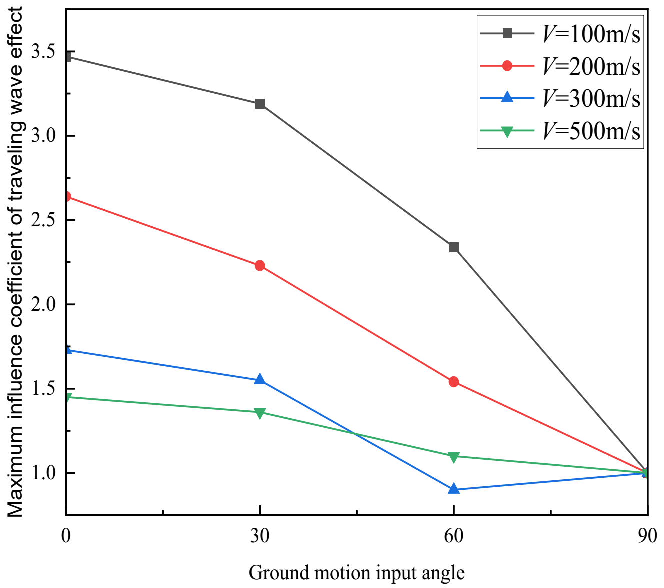
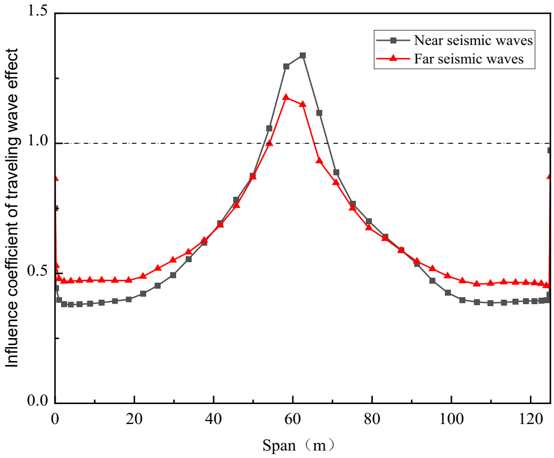


Fig. 9. Maximum influence coefficient of traveling wave effect under different ground motion input angles

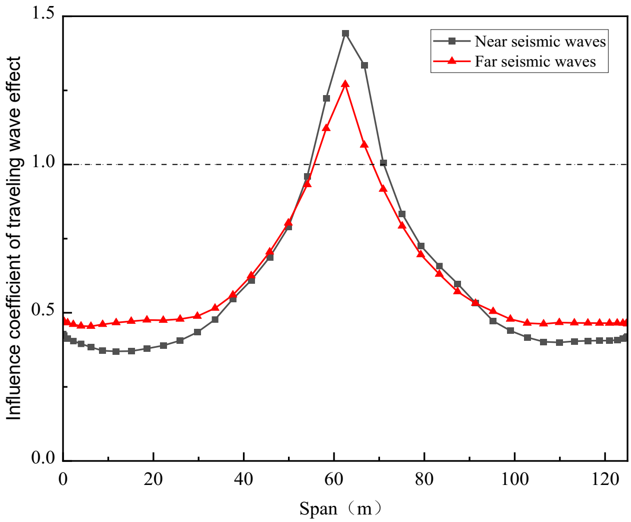
3.3 Influence of the epicentral distance on the traveling wave effect

Before the study, it is necessary to select suitable near and far seismic waves for calculation. Although there are multiple recorded natural waves, a comparison reveals variations in their seismic characteristics, such as effective duration and spectrum characteristics. It is challenging to control the epicentral distance as a single independent variable. Therefore, artificial synthetic seismic waves are used to simulate near and far seismic waves in this paper. In order to avoid the contingency of analysis results, the study simulates three near seismic waves and three far seismic waves separately, taking the average of the results from the three waves for calculation.

The apparent wave velocities of near and far seismic waves are selected as 100 m/s, horizontal (X) and vertical (Z) seismic waves are applied to the structure, and the calculation is conducted under multi-dimensional and multi-point seismic actions. The average of the three seismic waves are taken as the calculation results, which are compared with those under consistent excitation. Thus, the influence coefficient of the travelling wave effect of the long-span double-layer cylindrical reticulated shell structure under near and far seismic waves can be obtained, respectively. Taking the middle transverse bar of the shell as the research object, the traveling wave effect coefficients under near and far seismic waves are shown in Figure 10.



(a) Upper chord



(b) Lower chord

Fig. 10. Influence coefficient of traveling wave effect of the coal shed with the long-span double-layer cylindrical reticulated shell under near and far seismic waves

The analysis shows that the influence coefficient of the traveling wave effect under near seismic waves surpasses that under far seismic waves at the unfavorable bars in the mid-span, while this influence coefficient is smaller than that under far seismic waves at the favorable bars on both sides, indicating that the influence coefficient under far seismic waves is closer to 1. Therefore, for the long-span double-layer cylindrical reticulated shell structure, the influence of the traveling wave effect of near seismic waves on the structure is greater than that of far seismic waves. In the design of the structure, particular attention should be given to the influence of the travelling wave effect of near seismic waves on the structure.

4 Conclusions

This paper focuses on a coal shed with a long-span double-layer cylindrical reticulated shell with a span of 125 m and selects the El Centro wave, Taft wave, and artificial wave. Through the dynamic time history analysis under multi-dimensional and multi-point excitation, it studies the influence of seismic traveling wave effect on the long-span double-layer cylindrical reticulated shell structure under variations in seismic characteristics such as apparent seismic wave velocity, hypocenter direction, and epicentral distance. The main conclusions of this paper are as follows:

(1) The larger the apparent seismic wave velocity is, the smaller the influence of the seismic traveling wave effect on the structure will be. When $\Delta t < 0.15$ s, the influence of the traveling wave effect on the double-layer cylindrical reticulated shell structure can be ignored.

(2) A larger angle between the seismic wave propagation direction and the span direction of the structure results in a smaller influence of the seismic traveling wave effect on the structure. When considering the traveling wave effect, we should pay more attention to the earthquakes with slow propagation speed along the long-span direction of the structure.

(3) The traveling wave effect of near seismic waves has a greater influence on the structure than that of far seismic waves, so the influence of the travelling wave effect of near seismic waves on the structure should be paid more attention in the design of the long-span double-layer cylindrical reticulated shell.

Acknowledgements

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