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Dynamic characteristics of the railway ballast bed under water-rich and low-temperature environments

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ABSTRACT

Studying the dynamic characteristics and evolution laws of the ballast bed under low-temperature, rain and snow environments has practical significance for the driving stability of railways in alpine. In this paper, a full-scale ballasted track model was constructed in a programmable temperature control laboratory, and the frequency response function (FRF) curves of the ballast bed under different temperature and humidity conditions were measured. Then the vibration characteristics and the evolution laws of the ballast bed under different conditions were analyzed. The longitudinal transfer behavior and the dissipation of the vibration energy in the ballast bed under different humidity and temperature environments were discussed combined with the finite element method. The results show that the influence of temperature on the vibration characteristics of the ballast bed is not significant in the dry and water-rich environments, but the vibration characteristics of the ballast bed in the frozen environment change dramatically with the decrease of temperature. The vibration energy is harder to dissipate in the frozen ballast bed than in the dry and water-rich ballast beds, and the frozen ballast bed is more prone to be sudden damaged when a train passes due to the significant increase in its stiffness. Thus, the performance monitoring and emergency maintenance of the ballast bed in those environments should be strengthened.

1. Introduction

A ballast bed is a layered accumulation formed by a certain particle size distribution of crushed stones, which is widely used in the railway infrastructures in various complex environments [1]. Water and freezing disasters in railway constructions and operations, including in Norway, Sweden, Switzerland, Finland, China, Russia, Japan, Canada, Australia, Brazil and some parts of America, have received active attention from different countries [2–7]. In particular, the Qinghai-Tibet Railway in China, the Alaska Railway in the United States and the proposed Sichuan-Tibet Railway all across the cold regions, which require ballasted tracks to withstand the snow and low temperature [8]. The safe and high-speed running of a train requires high regularity of the track [9,10]. However, the poor drainage of the railway makes the subgrade soil intrusion into the ballast bed under train loads, causing disasters such as mud pumping and ballast bed hardening, and uneven stiffness of the track substructure [11–13]. In addition, soil freezing causes the frost heave of railway substructures and the uneven settlement of track structures. The snow and ice melt and the pore water pressure increases when the temperature rises, which cause the decrease of the stiffness and bearing capacity of the subgrade [14]. The volume of pore water in a ballast bed increases by 9% when it freezes [15]. If there is water intrusion at this time, ballast particles will freeze each other under the action of water, and the degree of frost heave of the ballast bed will be more intense [16].

Researches about the influence of rich-water, low-temperature and freezing environments on the dynamic performances of ballasted tracks can provide theoretical support for the construction, operation and maintenance of the ballasted tracks in rainy and alpine regions, and it also has important practical significance for the construction and operation of plateau railways such as the Sichuan-Tibet Railway and the Qinghai-Tibet Railway in China and the railways in severe cold regions such as Northern Europe. The drainage performance of ballast is affected by the particle size distribution and dirty materials [17]. Indraratna

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et al. [3] conducted constant permeability tests on the new ballasts with different proportions of fines by using a specially designed large-scale permeameter. They studied the relationship between fouling rates and the drainage characteristics of the ballasts, and found that a small increase in fine particles would significantly reduce the hydraulic conductivity of ballast. Qamhia et al. [18] conducted permeability tests of ballast samples with different degradation degrees on site by using the University of Illinois Constant Head Aggregate Permeameter (UICHAP). The results showed that the horizontal flowed through the ballast layer could be ignored under various common hydraulic gradients in the field. Pies et al. [19] monitored the thermal and water regimes of the ballasted track through the experimental stand of the Department of Railway Engineering and Track Management (DRETM), University of Žilina. The measured humidity values provide data basis for numerical simulations of the non-traffic loads on different track structures. Qie et al. [20] studied the relationship between the dirty rates and the drainage performance of ballast by using a permeameter with a diameter of 50 cm, and divided the dirty degree of ballast into four grades according to the permeability performance. A ballasted track faces the challenge of drainage in the water-rich area, and along the plateau railway, it will also suffer from the problems of snow and ice in the alpine environment. Nurmikolu et al. [2,21] proposed that the mechanical properties of the ballast bed in the low-temperature environment were different from those in general environments, which requires more attention. Latvala et al. [22] studied the susceptibility of subballast materials to convection, and the materials were railway ballast (31.5–63 mm), gravel subballast layer and 5–16 mm. The results showed that convection increased the thermal conductivity of railway ballast by several times, and the thermal conductivity of subballast used in Finland increased significantly when the moving medium contained water. Zhang et al. [23] studied the relationship between the ballast layer and the hydrothermal condition of subgrade in the permafrost region of Qinghai-Tibet Railway. The results showed that the large gaps and the grey covers of a ballast bed could effectively prevent the external heat from entering the subgrade, and played a good role in thermal insulation. However, things change when water invades. Akagawa et al. [24] observed the railway in northern Japan, and found that the uplifts of the ballasted track in cold regions was not only caused by the frost heave of the subgrade, but also sometimes the frost heave occurred in the ballast bed. Ižvolt et al. [25,26] used the 1:1 ballasted track experimental stand built outdoors and the SoilVision software to study the performance of frozen ballasted track, and compared the experimental results and numerical results. They put forward a design of nomogram for determining the necessary thickness of frozen subgrade surface layer based on the analysis results. Liu et al. [27] studied the mechanical properties of ballast-ice combinations in different frozen environments. They found that low temperature could improve the compressive properties of ballast-ice combinations, and the combinations changed from toughness to brittleness with the decrease of temperature. Liu et al. [28] also studied the resistance performances of the ballast bed in the water-rich, low-temperature and frozen environments. The results showed that the resistance of the ballast bed in dry low-temperature environment was lower than that in normal temperature conditions, and the resistance was highly sensitive to the change rate of temperature. When the displacement of sleeper was small, the icing ballast caused by the frozen environment could improve the resistance of ballast bed. The above researches explored the drainage, heat transfer and resistance characteristics of the ballast beds in water-rich, low-temperature and alpine environments, but did not consider the influence of those extreme climates on the dynamic characteristics of ballasted tracks.

With the development of the high-speed and heavy-haul railway, the influence of the vibration impact from the train on the ballasted track is more complex under the cold, rainy, and snowy conditions, which is also the key factor affecting the safety and regularity of railway [21]. Therefore, a full-scale ballasted track model was built in a programmable temperature control laboratory. The modal tests of the ballast bed under different humidity and temperature conditions were carried out combined with the impact excitation technology. Then the vibration characteristics and the evolution laws of the ballast bed under different conditions were analyzed. The longitudinal transfer behavior and the dissipation of the vibration energy in the ballast bed under different humidity and temperature environments were discussed combined with the finite element method. We hope this work can provide reference for the dynamic characteristics of the ballast bed in the complex environment.

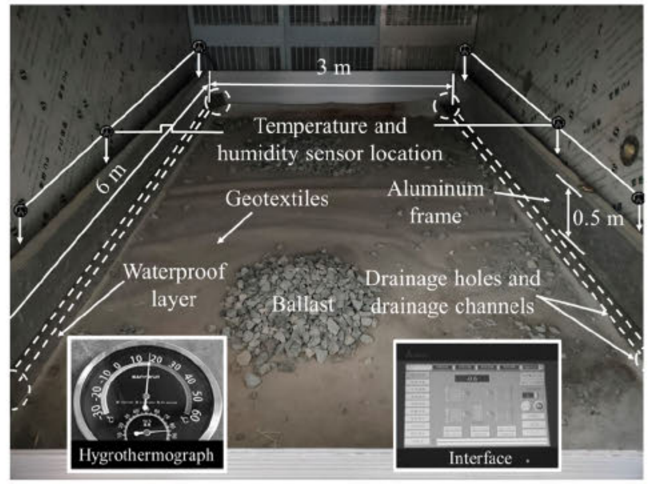

Fig. 1. A test laboratory with a programmable temperature-controlled environment.

2. Materials and methods

2.1. Programmable temperature control laboratory

The laboratory is built with 150 mm polyurethane plates (a kind of material with low thermal conductivity), and the space size is 6 m × 3.5 m × 3 m, with the temperature adjustment range of 50 °C to + 80 °C. A ballast box with aluminum alloy frame is installed in the laboratory. The configuration of the laboratory is shown in Fig. 1. The laboratory is equipped with real-time temperature and humidity sensors. In order to strengthen the monitoring of environmental parameters and improve the accuracy, temperature and humidity meters can be added locally according to the test requirements. The ballast box provides a relatively independent space for ballast to avoid the influence of the laboratory walls. The lower part of the ballast box is paved with a waterproof layer to avoid the intrusion of water. The waterproof layer is also used to guide water to flow through the pre-buried drainage channels to ensure that the ballast is in a free drainage state, so that the state of the ballast bed is as close as possible to the real working state.

According to the *Railway Applications-Track-Test Methods for Fastening Systems-Part 5: Determination of Electrical Resistance* [29], a circular sprinkler pipe was set up to simulate rainfall at the top of the laboratory, that was, the water-rich condition (rainfall intensity of 50 ± 10 mS/m). When simulating the water-rich state, the duration of rainfall was set to 2 h to make the surface layer and internal ballast particles of

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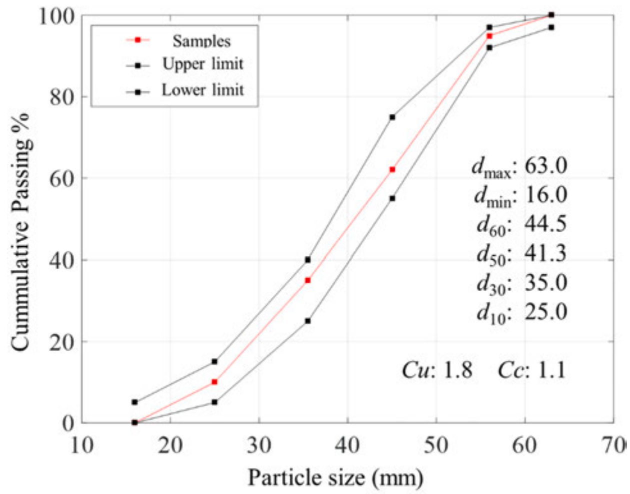

Fig. 2. Particle size distribution.

the ballast bed were fully wet (The preliminary test was carried out by human observation before the test. After the test, it was confirmed whether the particles inside the ballast bed was fully wet. If not, the test should be carried out again.). It should be pointed out that this work focuses on the variation law of the dynamic characteristics of the ballast bed under the water-rich condition, without considering the influence of rainfall values. Therefore, the ballast particles in the ballast bed were in a state of wetting but without the influence of water pressure with the drainage channels set up in the box.

2.2. Ballasted track model

The full-scale ballasted track model (Fig. 3) was constructed according to the standard of China's new Grade I railways [30,31]. The particle size distribution curve of the ballast bed is shown in Fig. 2. Four China's Type III prestressed reinforced concrete sleepers with shoulders were adopted in the model. The length of the sleeper was 2.6 m and the space between the sleepers was 0.6 m. The type of the rails was CHN60 (60.64 kg/m). Type II clips were used for the fastening system, with the torque of 150 N·m. The density of the ballast bed was 1.76 g/cm^3.

The slope gradient of the ballast bed is 1:1.75. When building the full-scale ballasted track model, the ballast bed was first divided into four layers, each layer was compacted by a compactor at least five times (Fig. 4 (a)). Then the superstructure of the track (the width and length of a sleeper are 0.32 m and 2.6 m. The sleeper mass is 380 kg, the sleeper spacing is 0.6 m, and railway gauge is 1.435 m.) was placed on the ballast bed (Fig. 4 (b)). Next, the ballast particles were continued to be stacked on the ballast bed formed the shoulders (Fig. 4 (c)). Secondary compaction of the ballast bed was carried out with the compactor after the tamping with a small tamping machine. The constructed ballasted track model is shown as Fig. 4 (d).

2.3. Test conditions

2.3.1. Types of test conditions

To make the tests close to the actual situations on site, the daily-

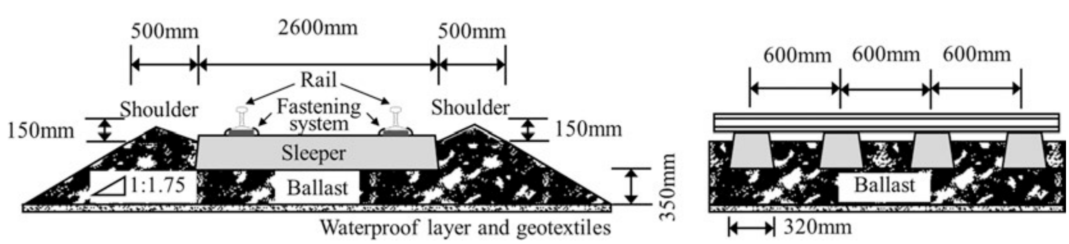

Fig. 3. Ballasted track model.

Fig. 4. Construction process of the full-scale ballasted track model.

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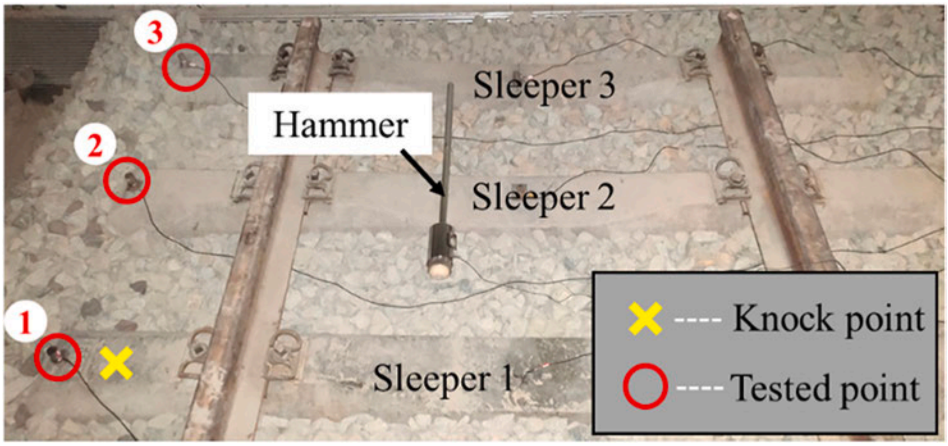

Fig. 5. Equipment layout.

average temperature along the Qinghai-Tibet Railway in recent three years was investigated. The results showed that the extreme low temperature was generally about 20 ± 5 °C. Therefore, the dry and water-rich (frozen) test conditions were set according to the normal temperature (20 °C), 0 °C, 10 °C, 20 °C, and 30 °C. The impact excitation tests of the ballasted track under water-rich and low-temperature environments were carried out based on those conditions. It should be noted that the dry condition in this study refers to the summer humidity is close to or less than 40%, and winter humidity is close to or less than 30% [32].

2.3.2. Temperature control duration

The temperature control duration directly determines the temperature state in the ballast bed. The temperature of ballast particles inside the ballast bed can be consistent with the ambient temperature when the duration is sufficient. Researches [28,33] have shown that the cooling in the ballast bed could be basically consistent with the ambient temperature and relatively stable after a constant cooling for a certain time (at least 24 h) in the laboratory environment. In order to ensure that the internal temperature of the ballast bed met the test requirements, the temperature setting of the laboratory was maintained for 36 h before the relevant tests were carried out.

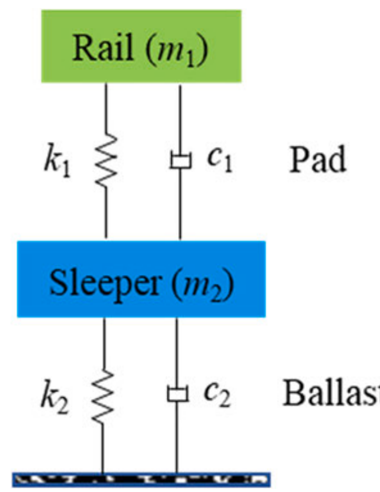

Fig. 6. Dynamic analysis model of the ballasted track system.

2.4. Impact excitation tests

The impact excitation technology, also called as “modal test”, is a non-destructive technology to study the dynamic characteristics of structures. Its main purpose is to identify the dynamic parameters (e.g. mass, stiffness, and damping) of the target structure, so that researchers can conduct targeted modal analysis of the structure [34]. Many researchers [35–39] have used the impact excitation technology to identify the state of ballasted track, indicating that the application of this technology in ballasted track is mature. In addition, Lam et al. [40,41], Hu et al. [42], and Mujib et al. [43] used the Bayesian method to analyze the vibration characteristics of the track structure based on the impact excitation technology. Therefore, we used the technology to explore the dynamic characteristics of the ballast bed under the complex environments.

The references [35,44–46] found that acceleration sensors installed at the end of sleepers provide high-quality data. Therefore, three inductively coupled plasma (ICP) acceleration sensors were mounted on the same sides of three adjacent sleepers with number 1, 2 and 3. The remaining sleeper in the track model provided a place for the tester to stand, so as to minimize the interference of human movement on the tested sleepers and ballast in the tests. The working frequency range of the sensor was 0.2–2.5 kHz (the sampling times per second can be set to 0.2–2.5 thousand), with the sensitivity of 500 mV/g, and the measuring range was 10 g. The hammer was a nylon head hammer with an ICP force sensor. The measuring range of the sensor is 125 kN and the sensitivity is 0.0417 mV/N (When the same energy is used to knock the specimen, different hammers can stimulate a variety of frequency bandwidth (the softer the hammer, the wider the pulse, the narrower the frequency bandwidth).). The rubber hammer is soft, and its measurement frequency is low. The measurement frequency of steel hammer is high. The measurement frequency of nylon hammer is between the above two hammers. According to the research and practice results in References [35–38,44], it is applicable to test the vibration frequency of 0–1500 Hz for the sleeper-ballast bed system of ballasted tracks. In addition, the final pulse duration is also related to the stiffness of the impacted specimen. The impact energy is distributed in a wide frequency band when the hard hammer is used, which means that the power spectral density of the excitation may be low in some cases, or

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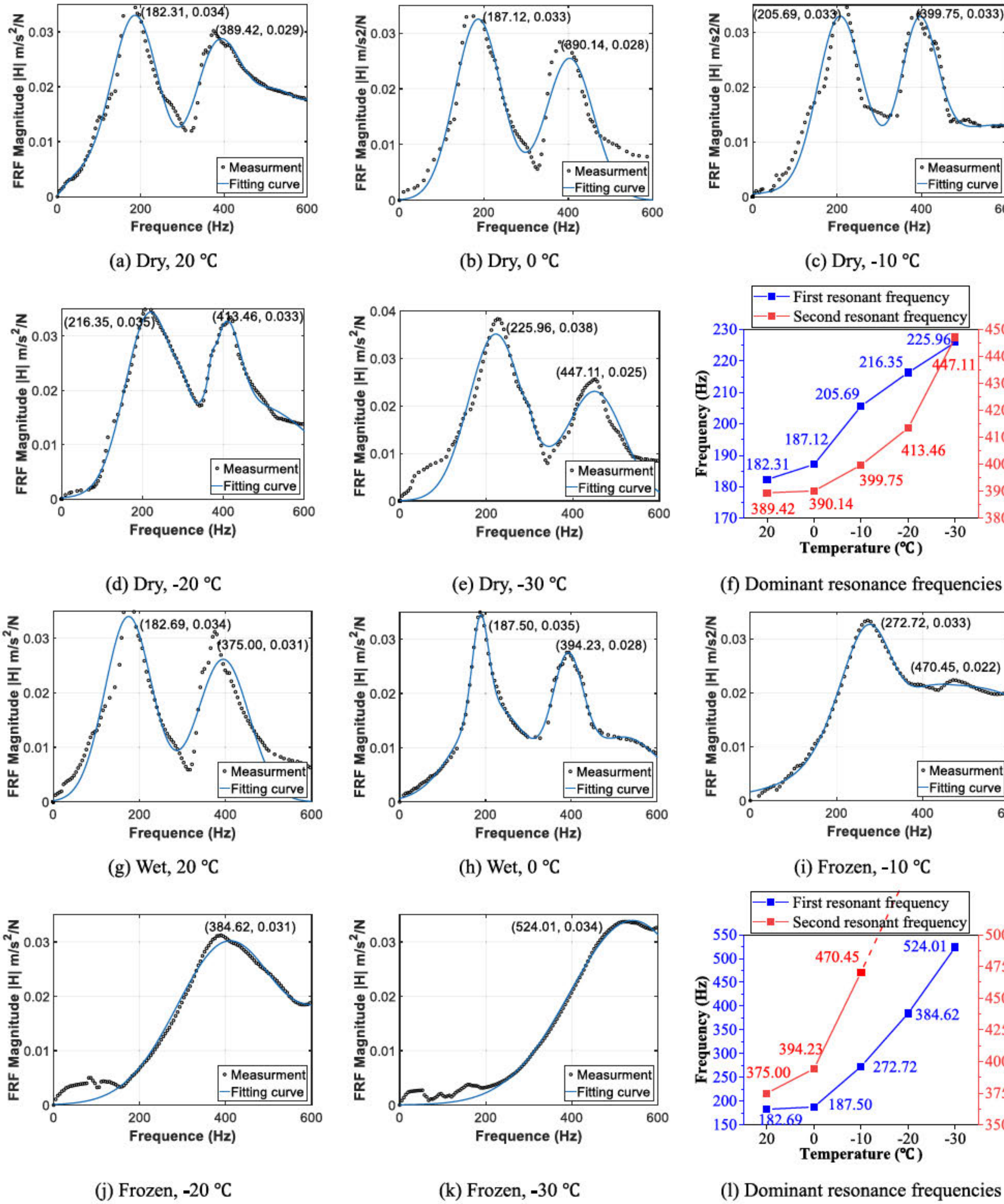

Fig. 7. Dynamic characteristics of the ballast bed under different temperature and humidity conditions.

even too low to excite the vibration mode and/or resonance of the specimen. Therefore, we chose a nylon hammer according to the performance between the hammer and the concrete sleepers. A 24-bit high-precision analog-to-digital converter with a sampling frequency of 12.8 kHz (a set of commercial instruments of the Coinvd company) was used to collect data. The test instruments and sensors were arranged as shown in Fig. 5. The head of Sleeper 1 was impacted by the hammer three times during one group of the tests (At least three times, the built-in program of the DASP software created by the Coinvd would automatically analyze the correlation and reliability of the three results. If the requirements were met, the curve of the frequency response function (FRF) would be given. If not satisfied, the software would prompt the sleeper should be impacted again.). The vibrations were picked up by the acceleration sensors.

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Table 1
Damping and stiffness of the track structure.

Track state		Rail mass m_1 (kg)	Pad stiffness k_1 (10^8N/m)	Pad damping c_1 (10^4 Ns/m)	Half sleeper mass m_2 (kg)	Bed stiffness k_2 (10^8N/m)	Bed damping c_2 (10^5N s/m)
	Theoretical value	36–60*	-	-	125.00	-	-
Dry (°C)	20	50.96	1.47	2.53	125.03	4.58	3.20
	0	50.14	1.89	3.24	125.12	4.33	3.43
	−10	50.61	3.15	3.65	125.77	4.72	3.76
	−20	50.17	3.73	3.88	125.43	4.43	3.51
	−30	50.60	4.18	3.96	125.12	4.54	3.45
Wet or frozen (°C)	20	50.77	1.45	2.47	126.10	4.75	3.00
	0	50.83	1.96	3.31	125.34	4.51	3.53
	−10	51.26	3.02	3.74	125.13	8.93	3.01
	−20	51.17	3.55	3.83	125.50	10.79	2.76
	−30	50.39	4.24	4.01	125.25	13.50	2.35

* The weight of the rail is 60.64 kg per meter. It can be considered that the mass of the rail shared by per half sleeper is 60.64 kg/m × 0.6 m = 36.684 kg if we analysis the half-sleeper model from a discrete point of view (the red area in Fig. 8, discrete type). However, the band-shaped rail is connected with many sleepers through the fastener system to form a framed whole. Because of the constraint from the sleepers on both sides, the vibration mass of one section of rail (0.6 m) should be greater than 36.684 kg when the it participates in the vibration (the blue area in Fig. 8, continuous type).

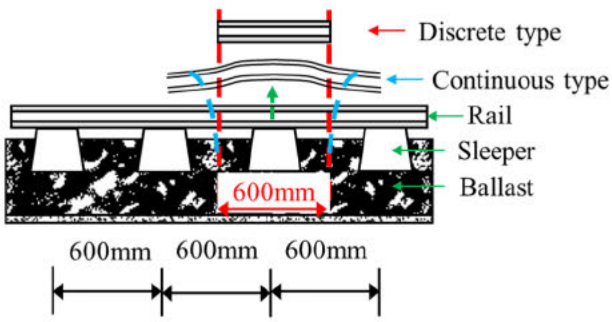

Fig. 8. Rail mass borne by half sleeper.

3. Results and discussions

3.1. Two-degree-of-freedom model (2DOF)

The two-degree-of-freedom mass-spring model (2DOF) [34] is widely used in the dynamic identification of railway track [35,44,47]. The dynamic analysis model of a ballasted track system can be established as Fig. 6 according to the characteristics of the structure (a half-sleeper model of the track).

The acceleration FRF of the 2DOF system in Fig. 6 can be obtained by the fast Fourier transform (FFT), as shown in Eq. (1) [36].

$$H_{11}(f) \quad \frac{\sqrt{\left[k_1+k_2 \quad 4\pi^2f^2\right]^2+\left[2\pi f(c_1+c_2)\right]^2}}{\sqrt{\left[(k_1 \quad 4m_1\pi^2f^2)(k_2 \quad 4m_2\pi^2f^2) \quad 4\pi^2f^2(k_1m_1+c_1c_2)\right]^2+4\pi^2f^2\left[k_1c_2+k_2c_1 \quad (m_1(c_1+c_2)+c_1m_2)4\pi^2f^2\right]^2}},$$

where f is frequency (Hz) and H_{11} (f) is FRF (m/s^2/N). m_1, k_1, c_1, m_2, k_2 and c_2 are the unknown parameters of the 2DOF. The parameters of the ballasted track system can be identified by the least square method based on Eq. (1) and the test data. To ensure the validity of the test data, the data of the coherence function $C_{xy}(k)$ more than 0.8 was chosen for analysis [46].

3.2. Effects of different temperature and humidity on the damping and stiffness of ballast bed

Grassie et al. [49] found there were two dominant resonances in the range of 0–1000 Hz. The first resonant frequency is the resonance of rails and sleepers on a ballast bed, and the resonance frequency is about 100 Hz. The second resonant frequency is the inverse resonance between rails and sleepers on a ballast bed, and the resonance frequency is about 300–500 Hz, which mainly depends on the performance of pads. Therefore, the range of 0–600 Hz was selected as the effective range for analysis in this paper.

In order to explore the influence of temperature and humidity on the vibration characteristics of the ballast bed, the FRF of Sleeper 1 under different temperature and humidity environments were analyzed by using the data measured from Sleeper 1 (Fig. 7). The corresponding damping and stiffness of the ballast bed were obtained by the parameter identification method, as shown in Table 1 and Fig. 9. The scatter points in Fig. 7 are the measured results of the FRFs of Sleeper 1 under different conditions, and the curves are the FRF curves obtained by using Eq. (1) for parameter identification.

It can be seen from Fig. 7 that there are two dominant resonant frequencies in the ballasted track structure at different temperatures in the dry environment in the range of 0–600 Hz, which are 180–230 Hz and 380–450 Hz, respectively. The dominant resonance frequency of 180–210 Hz is different from Grassie's conclusion [49], which may be due to the different structural forms of the two tracks. The first and second resonant frequencies of the structure in dry and water-rich (frozen) environments all increase with the decrease of temperature. However, the influence of the frozen environment on the resonant frequency is more significant compared with that of the dry environment. Especially at 20 °C and 30 °C, the second dominant resonance frequencies exceed 600 Hz. In addition, the resonance frequencies at 20 °C and 0 °C in dry and water-rich environments are similar. It is deduced that when the temperature is not lower than 0 °C, the influence of water-rich state (non-excess-water state) on the vibration characteristics of ballasted track is not significant.

In order to further clarify the influence of low temperature and rich

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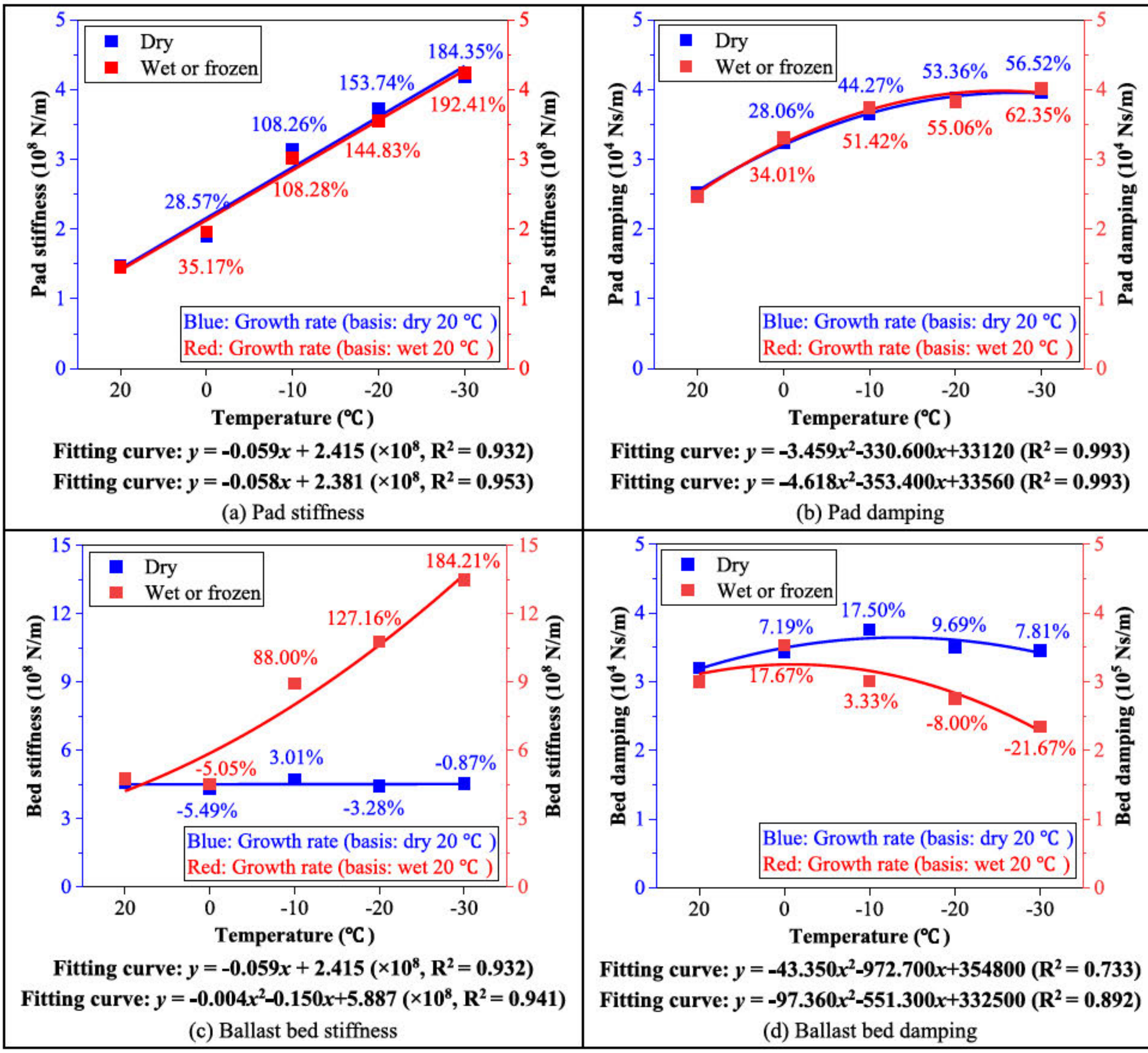

Fig. 9. Growth rates of the damping and stiffness under different temperature and humidity conditions.

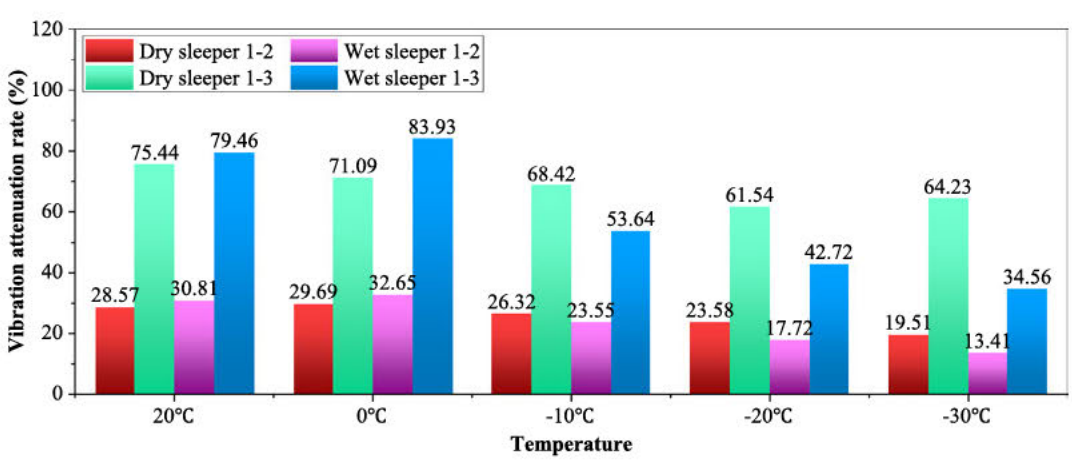

Fig. 10. Longitudinal vibration attenuation rates of the ballast bed under different temperature and humidity.

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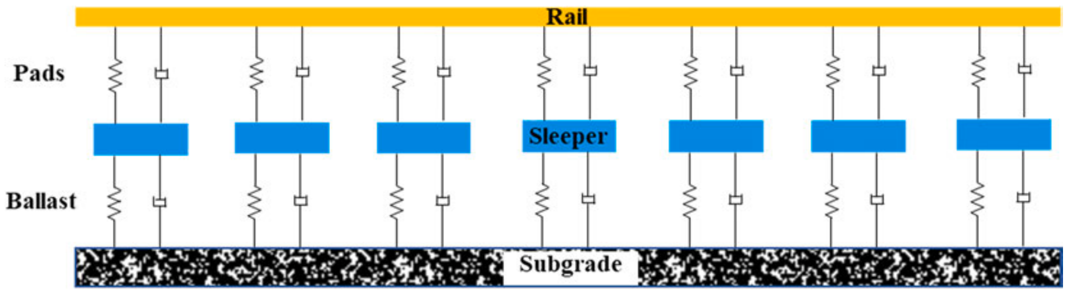

Fig. 11. Two-layer track model (discretely supported).

water on the dynamic characteristics of ballasted track, the FRFs of the ballasted track structure under different test conditions were obtained based on the least square method, as shown in Table 1. Then the changes of the pad stiffness, pad damping, ballast bed stiffness and ballast bed damping under different test conditions were analyzed, as shown in Fig. 9.

It can be seen from Table 1 that the parameter identification results of the track structure are close to the known theoretical values, so the parameter identification results are effective. Further analysis shows that the stiffness and damping of the pad increase with the decrease of temperature, which are the same as the conclusion in the existing research [48]. However, the values and trends of stiffness and damping of the pad in this study are different from the existing research results, which may be caused by the difference of the types and materials of rubber pads. In addition, it should be noted that the values and trends of stiffness and damping of the pad in dry and water-rich (frozen) environments are generally consistent (Fig. 9(a) and (b)). The above results show that the performance change of the pad is not sensitive to water and ice at normal temperature. It can be seen from Fig. 9(c) and (d) that the stiffness and damping of the ballast bed show small fluctuations with the decrease of temperature in the dry environment (The maximum change rate of ballast bed stiffness is 5.49%, and the maximum change rate of ballast bed damping is 17.50%). In the water-rich environment, the ballast bed stiffness decreases with the decrease of temperature, and the ballast bed damping increases with the decrease of temperature. The reason is that the mud formed by fine particles and water in the ballast bed can reduce the interlocking and friction between ballast particles under the combined action of water and low temperature (not lower than 0 °C). Moreover, the mixture of the fine particles and water is easier to fill the gaps between the ballast particles than the dry fine particles, which plays a 'lubrication' role between the ballast particles. In the frozen environments, the ballast bed stiffness increases with the decrease of temperature, and the ballast bed damping decreases with the decrease of temperature. This is because the lower the temperature is, which makes the water on the ballast surface condense into ice without rushing out, and the thicker the ice between the ballast particles is. The larger the surface area of ballast wrapped in by ice is, the stronger the bond strength forms. In addition, the characteristics between ballast and ice make it easier to form the mixed 'big particle' with ballast particles and ice layer as main components. This kind of 'big particle' is restricted by the surrounding 'big particles', so it is difficult to move and rotate [28].

In summary, when the temperature is higher than 0 °C, whether the ballast bed is wet or not has little effect on the vibration characteristics of the track structure, and the ranges of the dominant resonance frequencies are generally the same. When the temperature is lower than 0 °C, the track bed wetting or not has significant effect on the vibration characteristics of the track structure, and the ranges of the dominant resonance frequencies are quite different. Special attention should be paid to the damage of the ballasted track under high-frequency train loads, especially in the extremely low-temperature frozen environment.

3.3. Longitudinal transmission of the vibration in the ballast bed under different temperature and humidity

Dynamic characteristics of the ballast bed under different temperature and humidity were tested by the method of "single-point excitation and multipoint pick-up". The hammer was used to knock the excitation

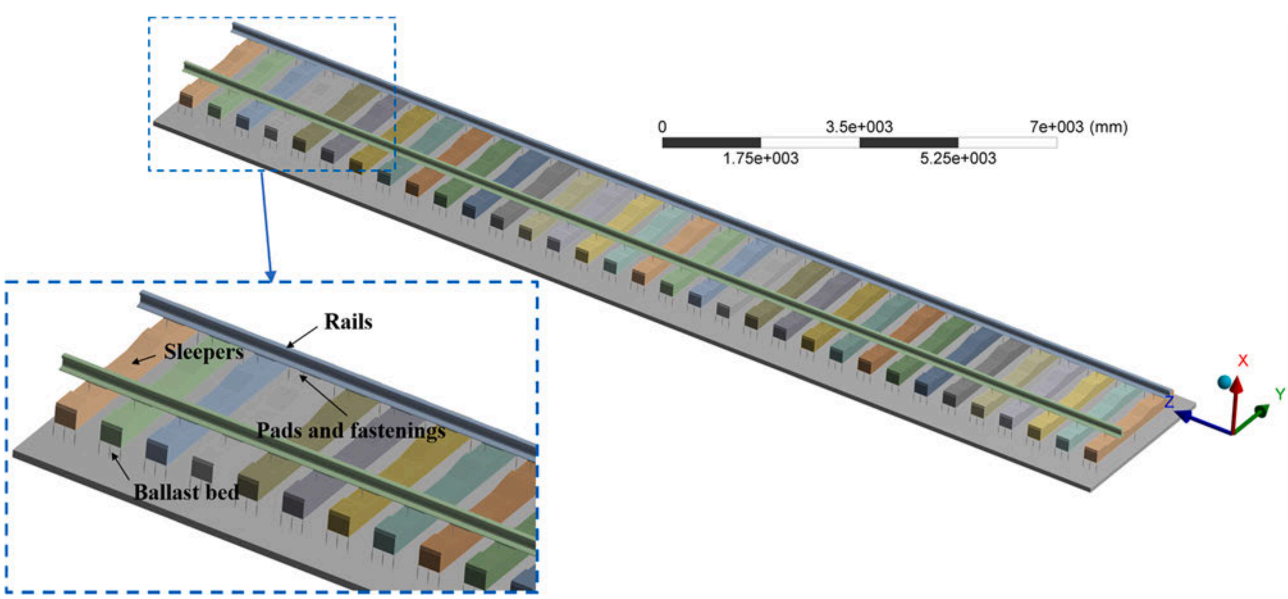

Fig. 12. Finite element model of the track structure.

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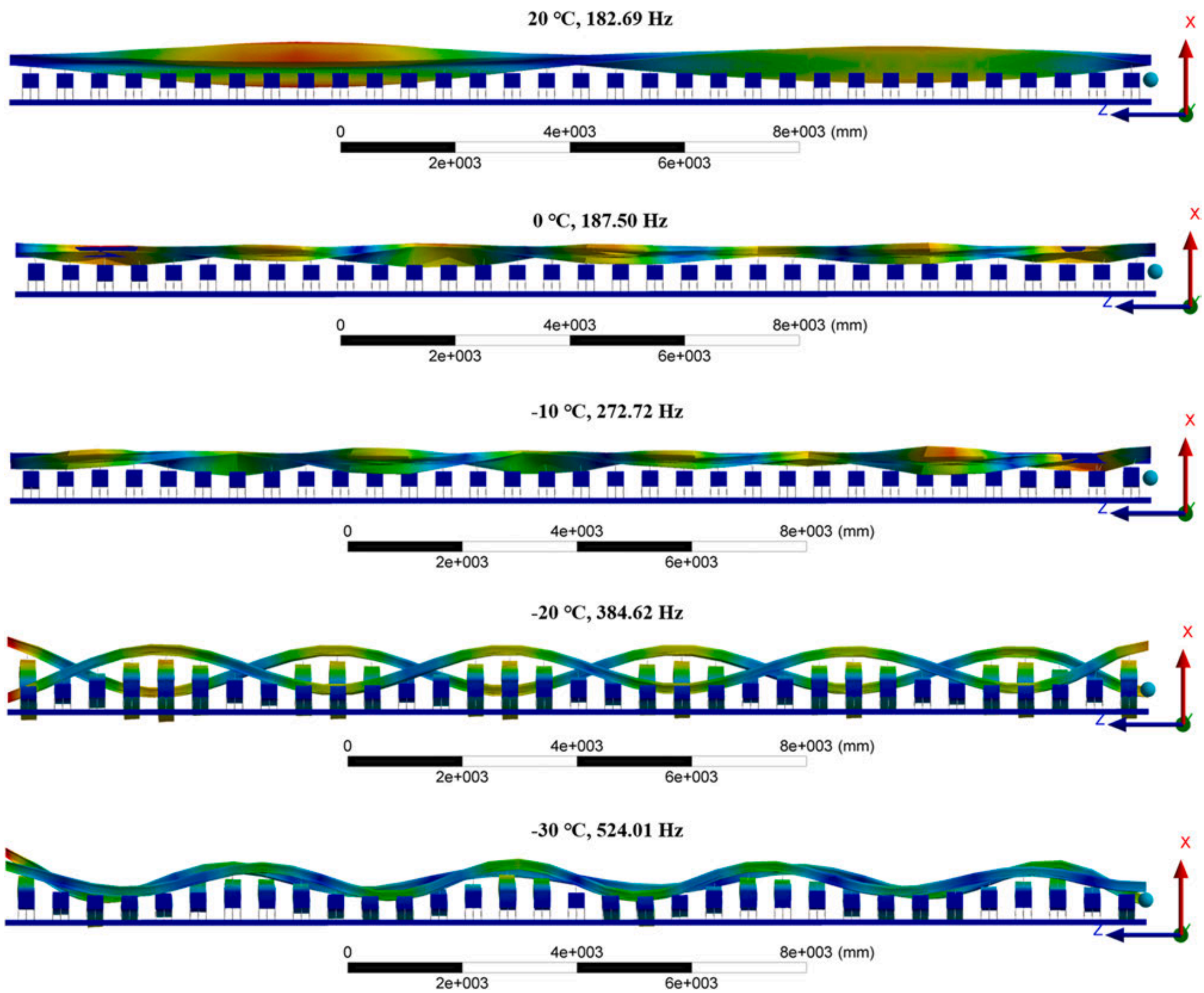

Fig. 13. Modal shapes of the first dominant resonant frequencies of the track structure in the frozen environments.

point on the left end of Sleeper 1 in Fig. 5, and the vibration accelerations of the adjacent three sleepers were measured by the acceleration sensors. The FRFs of vibration were obtained in the modal space. The vibration energy of the ballasted track of the first resonant frequency was abundant compared with the other resonant frequency (Fig. 7). Therefore, the first resonant frequency of Sleeper 1 in each test condition was selected as the analysis basis to explore the transmission and dissipation of the vibration energy between adjacent sleepers.

The longitudinal vibration attenuation rate of ballast bed is defined as Eq. (2) [39]. The attenuation rates of the ballast bed in each test condition is shown in Fig. 10.

$$R = \frac{V_1 - V_i}{V_1} \tag{2}$$

where R is the longitudinal vibration attenuation rate, and V_1 is the FRF value corresponding to the first resonant frequency of Sleeper 1. V_i is the FRF value of the adjacent Sleeper i at first resonant frequency of the Sleeper 1. The larger the R is, the weaker the longitudinal transmission capacity of vibration between sleepers is, that is, the stronger the damping capacity of the ballast layer between sleepers is.

It can be seen from Fig. 10 that in the dry environment, the longitudinal vibration transmission of the ballast bed increases (R decreases) and fluctuates locally with the decrease of temperature. The maximum difference of the longitudinal vibration attenuation rate of Sleeper 1–2 is 10.18%, and that of Sleeper 1–3 is 13.90% in each test condition. In the water-rich environment, the longitudinal vibration transmission of the ballast bed decreases with the decrease of temperature (R increases), but the change is not significant. The longitudinal vibration attenuation rate between Sleeper 1 and Sleeper 2 decreases by 1.84%, and the that between Sleeper 1 and Sleeper 3 decreases by 4.47% when the temperature decreases from 20 °C to 0 °C. Combined with the analysis in Section 3.2, it can be found that the influence of water-rich state (non-excess-water state) on the vertical and longitudinal vibration characteristics of the ballast bed is not significant when the temperature is higher than 0 °C. The longitudinal transmission performance of the vibration in the ballast bed increases with the decrease of temperature (R decreases) in the frozen environment. The vibration attenuation rate between Sleeper 1 and Sleeper 3 is only 13.41% when the temperature is −30 °C. Combined with the analysis in Section 3.2, we can see that the vibration energy is more difficult to dissipate in the frozen ballast bed than in a dry or water-rich one. Meanwhile, due to the significant increase in the stiffness of the ballast bed during freezing (about 180% increase at −30 °C), the frozen ballast bed is more prone to sudden damage when trains pass. Therefore, the performance monitoring and emergency maintenance of the ballast bed in frozen environment should be strengthened.

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4. Numerical simulations of the longitudinal transmission characteristics of vibration

The above results and analysis show that the low-temperature frozen environment will significantly affect the stiffness and damping of the ballast bed, and improve the integrity of the ballast between sleepers. Thereby, the transmission characteristics of vibration in the ballast bed and track frame were affected. In order to further explore the influence of frozen environment on the dynamic performance of ballasted track structure, the stiffness and damping values of the track structure in Section 3.2 were utilized in numerical simulations.

4.1. Establishment of numerical models

The values of main parameters were set based on the track model in Section 2.2. Rail: density of 7800 kg/m^3, elastic modulus of 2.06×10^{11} Pa, Poisson 's ratio of 0.3. Sleeper: density of 1320.8 kg/m^3, elastic modulus of 3.00×10^{10} Pa, Poisson 's ratio of 0.18. The sleeper space is 0.6 m. The stiffness and damping of fastening system were set according to Table 1. A solid model of 33 sleepers [51,52] was established by the improved elastic-supports continuous beam model and finite element method. This improved two-layer model adds a layer that can simulate the rubber pads, sleepers and ballast on the single-layer model. In the two-layer model shown in Fig. 11, the ballast, fastenings and pads are massless [53,54], but can also be included by adding additional layers [55].

The model built in the commercial software ANSYS [56] is shown in Fig. 12. The bottom of the model was fixed to achieve the purpose of support and limit. The displacement and rotation of each end of the rails were limited to simulate the effect of a continuously welded rail track (CWR track). In addition, the lateral motions of the sleepers were limited. Because we focused on the longitudinal transmission characteristics of vibration in the track structure and needed to exclude the interference in other directions.

4.2. Analysis of the numerical simulations

The stiffness and damping values of the ballast bed under the wet and frozen environments in Table 1 were selected and simulated in turn by the numerical model in Section 4.1. The modal shapes of the ballasted track at the corresponding first dominant resonant frequencies (20 ℃, 182.69 Hz; 0 ℃, 187.50 Hz; 10 ℃, 272.72 Hz; 20 ℃, 384.62 Hz; 30 ℃, 524.01 Hz) under different wet and frozen conditions are shown in Fig. 13.

Of course, it should be admitted that there are some differences between the results of simulations and the actual, but we can still find some potential laws through the simulations.

It can be seen from Fig. 13 that the vibration modes at the first dominant frequency of the ballasted track in 20 ℃, 0 ℃, 10 °C wet or frozen environment are mainly the torsional deformation of rails, while the torsional deformation of rails and the bending deformation of sleepers are the main in 20 °C and 30 °C frozen environments. The above results confirm the vibration and transmission characteristics of the ballasted track in the frozen environments in Chapter 3. Concretely speaking, the energy of the superstructure of ballasted track after being subjected to impact loads is not easy to dissipate in the track structure with the decrease of temperature. Most of the vibration transmits in the superstructure and the frozen ballast bed, which results in more violent and lasting vibration of the superstructure. Considering the high-frequency vibration of rails and sleepers when the train passes, the monitoring of the frozen ballasted track should be strengthened in the operation of railways to avoid the safety problems caused by the poor contact between sleepers and the frozen ballast bed.

5. Conclusions

In this paper, a full-scale ballasted track model was built in a large temperature-control laboratory. The modal tests of the ballast bed under different humidity and temperature conditions were carried out combined with the impact excitation technology. The evolution law of the vibration characteristics of the structure with humidity and temperature was analyzed, and the longitudinal transmission of vibration between sleepers under different humidity and temperature environments was discussed. The main conclusions are as follows.

(1) The influence of frozen environment on the resonance frequency of the track structure is more significant than that of dry environment (The second dominant resonance frequencies exceed 600 Hz at 20 °C and 30 °C.). When the temperature is higher than 0 °C, the influence of water-rich state (non-excess-water state) on the vertical and longitudinal vibration characteristics of the ballast bed is not significant.
(2) The stiffness and damping of the ballast bed show small fluctuations with the decrease of temperature in the dry environment. In the water-rich environment, the 'lubrication' of mud makes the stiffness of the ballast bed decrease with the decrease of temperature, and the damping of the ballast bed increase with the decrease of temperature. In the frozen environment, the stiffness of the ballast bed increases with the decrease of temperature, and its damping decreases with the decrease of temperature.
(3) The vibration modes at the first dominant frequency of the ballasted track in 20 ℃, 0 ℃, 10 °C wet or frozen environment are mainly the torsional deformation of rails, while the torsional deformation of rails and the bending deformation of sleepers are the main in 20 °C and 30 °C frozen environments.
(4) Compared with dry and water-rich environments, vibration energy is more difficult to dissipate in the frozen ballast bed. Moreover, due to the significant increase in the stiffness of the ballast bed during freezing (about 180% increase at 30 °C), the frozen ballast bed is more prone to sudden damage when the train passes. The performance monitoring and emergency maintenance of ballast bed in frozen environment should be strengthened.

CRediT authorship contribution statement

Jianxing Liu: Conceptualization, Data curation, Formal analysis, Writing – original draft. **Zhiye Liu:** Methodology, Resources. **Ping Wang:** Investigation, Software, Resources. **Lei Kou:** Investigation. **Mykola Sysyn:** Supervision, Validation, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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