Influences of Stiffness of Rail Pads on System Dynamic Performances of Heavy Haul Railway

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Abstract. In order to solve the problem that the track structure is oversimplified in the dynamics study of heavy haul railway, a wagon vehicle-track coupled dynamic model is proposed in this paper. The track structure is more detailed and is modelled by a composite double-layer dynamic model. The upper layer is composed of two rails and the lower layer is composed of many sleepers. The rails are connected with sleepers by the rail pads. This more detailed model is then used to study the influences of the stiffness of the rail pads on the system dynamic performances of heavy haul railway. The results reveal that the proposed model is more practical to study the dynamic problems of heavy haul railway, and the model is able to subtly analyze the dynamic influences of local structure on the wagon vehicle-track coupled dynamic system. The results also shows that the stiffness of the rail pads has a great impact on the vertical wheel/rail force, the dynamic responses of the wagon and the vertical displacement of the rail. The smaller stiffness of the rail pads will worsen the wear process of the rail and aggravate the vibration displacement amplitude of the fasteners by increasing the vibration of the rail. Therefore, an appropriate stiffness of the rail pads is of great significance to extend the service life of the track and to reduce the maintenance and operation cost.

Keywords: Composite double-layer dynamic model · Wagon vehicle-track coupled dynamics · Track structure · Stiffness of rail pad · Heavy haul railway

1 Introduction

The rail pad is an important elastic component of the ballast track and also plays an important role in vibration and noise reduction of the wheel/rail coupled dynamic system. In order to meet the needs of the freight transportation, the axle load of the heavy-haul wagon is more and more heavy and the train velocity is also speeded up. This has greatly worsened the load conditions of the track structure, which will aggravate the aging rate of the rail pads, intensify the damage of the track structure, increase the railway maintenance and even endanger the running safety [1].

The existing research results show that the failure coefficient of track structure is proportional to the square root of the stiffness of the rail pads, and the provision of elastic the rail pads can effectively reduce the wheel/rail interaction, slow down the

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pulverization of the ballast and decrease the railway maintenance. So an appropriate stiffness of the rail pad is of great significance to improve dynamic performances of the train and the track structure. It is necessary to study the influence of the stiffness of the rail pad on dynamic performances of the vehicle and the track. Shi et al. used the NUCARS software to establish a wagon vehicle-track coupled dynamics model, in which the rail and the sleeper were modelled by the discretely supported Euler-Bernoulli beam, and the track bed and the subgrade were simplified as many parallel damping-spring units. This model reduces the computational complexity and also has high accuracy [2]. Xu and Zhai analyzed the influence of different stiffness of the rail foundation on vibration and noise of the wheel/rail system induced by the wheel/rail surface roughness [3]. Tu used the vertical vehicle-track coupled dynamic model to demonstrate the impact of fasteners and the rail pads on the dynamic response of the wheel/rail system [4]. Luo et al. established a finite element model of the rail pad using Abaqus software to analyze its dynamic response and fatigue performance [5, 6]. Chang developed a finite element model of the track structure of the heavy haul railway using ANSYS software. In the model, the rail pads were simplified as spring-damping units and the concrete sleepers were discreted as beam elements. He focused his research on influences of the rail type, the stiffness of the rail pads and the state of the track bed on the static performance of track structure [7]. Xu and Cai proposed a spatial train-ballast track-subgrade coupled dynamic model which considered the dynamic properties of the rail pads, sleepers and the subgrade. Using the model, they obtained the dynamic responses characteristics of the track and the dynamic characteristics of the deformation and stress of the track bed surface [8]. Lundqvist used the finite element method to establish a dynamic analysis model of the track considering the aging deformation of the rail pads and the hanged sleepers. The model is used to study the effect of the stiffness of the rail pads and the hanged sleepers on the dynamic vehicle-track interaction [9]. Shu et al. proposed a new infiltrated wheel/rail contact model considering the deformation of wheel/rail contact, which led to a more realistic vehicle-track coupled dynamic model [10]. By the numerical simulation and the test of the track of hundreds of kilometers, Li and Berggren studied influences of the vertical stiffness of the components of the track on the dynamic performances of the track system and investigated the global matching problem of the vertical stiffness of the components of the track [11]. Huang established the dynamic simulation model of the heavy-haul wagon using SIMPACK software to analyze influences on the dynamic wheel/rail interaction by the dynamic parameters of the wagon and the track, such as the wheel/rail friction coefficient, the stiffness of the rail pads and the rail cant [12]. Based on the theory of vehicle-track coupled dynamics, Wang used the large-scale computer simulation soft TTSIM to studied influences of the key parameters of the track and the vertical and lateral support stiffness of the rails on dynamic performances of the wheel/rail interaction of curve track [13]. Based on the theory of vehicle-track coupled dynamics, Zhai took into account the impact of three aspects of the vehicle, the track, wheel and the wheel/rail interaction interface the orbital structure of the dynamic response to study the dynamic responses of the track, which broke through the limitations of the simplify of the traditional methods [14].

In the above studies, the model of the track is often too simplified to accurately reflect the dynamic performances of the heavy haul railway. Additionally, most of the studies involving the stiffness of the rail pads put focus on its influences on the dynamic responses of the track structure, and rarely studied its effect on the dynamic performances of the whole vehicle-track coupled system. Aiming at the shortcomings of the above researches, this paper proposes a more practical wagon vehicle-track coupled dynamic model in which the track structure is more detailed and is modelled by a composite double-layer dynamic model. The wagon of 30t axle load is token as the study object to study the influences of the stiffness of the rail pads on the dynamic performances of the whole heavy haul wagon vehicle-track coupled dynamic system.

2 Composite Double-Layer Dynamic Model of Track

In most of existing researches, the track structure is often simplified as a single-layer structural model, as shown in Fig. 1. The main idea of this model is that all of the rails, sleeper, track bed, subgrade and other structures are regarded as a rigid body (called as integrated track in Fig. 1) and the stiffness and damping of the structure and all elastic components are integrated as the spring-damping units supporting the integrated track. So this model can be regarded as a single-layer structural model. The actual track is very complicated and each component of the track has stiffness and damping. But the single-layer structural model uses lumped parameterization for all the structural components such as rails, sleepers, track bed and subgrade and all the elastic damping components such as fasteners and the rail pads. This simplification can't reflect the practical dynamic performances of the track, especially for the heavy haul railway.

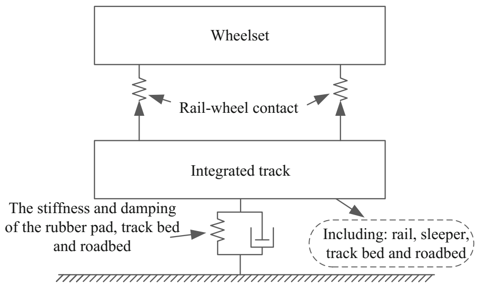

Fig. 1. The single-layer structural model of the track structure

In this paper, the track structure is more detailed and is modelled by a composite double-layer dynamic model. Then a more practical wagon vehicle-track coupled dynamic model is proposed based on the theory of vehicle-track coupled dynamics. Lastly the wagon vehicle-track coupled dynamic model is used to study the influences of the stiffness of the rail pads on the dynamic performances of the whole heavy haul wagon vehicle-track coupled dynamic system.

The composite double-layer dynamic model of the track structure is developed on the basis of the single-layer structural model, as shown in Figs. 2 and 3. The basic idea is that the track structure is more detailed and is modelled by a composite double-layer

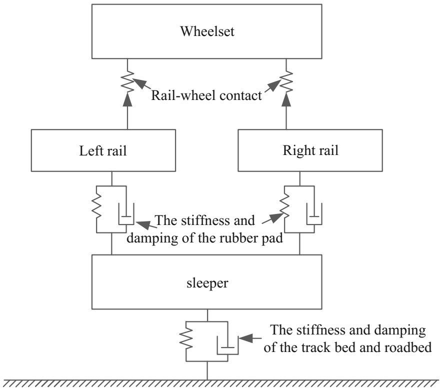

Fig. 2. Composite double-layer structural model

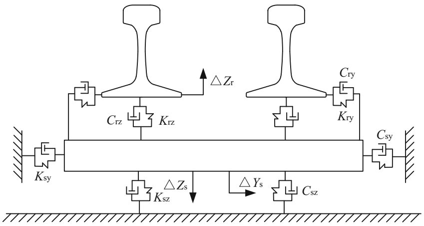

Fig. 3. Composite double-layer dynamic model of the track structure of the track structure

dynamic model. The upper layer is composed of two rails and the lower layer is composed of many sleepers. The rails are connected with sleepers by the rail pads and fasteners. The track bed and the subgrade are integrated as the elastic foundation under the sleepers. So in the double-layer dynamic model, the rail is separated from the sleeper and the interaction between the rail and the sleepers are more practical which is able to accurately simulate the role of the rail pads. Meanwhile the wheel/rail contacts also need to be modified in new model.

3 Rang of the Stiffness of the Rail Pads

As the existing railway lines is generally the mixed passenger and freight railway, therefore, the stiffness of the pads is generally in the range of 55–80 MN/m [16]. For the Daqin line of the largest annual transport capacity in China, according to the field test in the Datong line [17], the relationship between the stiffness of the rail pads and the total transport volume is as shown in Fig. 4.

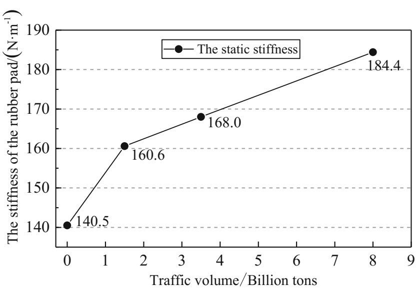

Fig. 4. Observation data of static stiffness of rail pads

In view of the above, considering the development trends of axle load and running speed creasing and in order to more comprehensive study of the influences of the stiffness of the rail pads on the dynamic performances of the whole heavy haul wagon vehicle-track coupled dynamic system, the range of the stiffness of the rail pads is 40–200 MN/m, and the velocity of the wagon vehicle is 100 km/h.

4 Numerical Analysis

4.1 Influences of the Stiffness of the Rail Pads on Dynamic Performances of Car Body

In China, the specification, *railway vehicles—Specification for evaluation the dynamic performance and accreditation test* (GB 5599-85), provides the vibration acceleration limit and the stability index level of the vehicle [18]. The vertical and lateral stationarity of the car body use the evaluation scale and the value less than 4.25 is the qualified level. The vibration acceleration limits of the car body are defined as: the vertical and lateral vibration are not more than 0.7 g and 0.5 g.

It can be seen from Fig. 5 that the stiffness of the rail pads has little effect on the vertical vibration acceleration and the stationarity of the car body. With the stiffness of the rail pads increasing, the maximum value of the vertical vibration acceleration of the car body varies in the range of 3.03–3.18 m/s^2, and the maximum value of the stationarity of the car body is in the range of 3.65–3.68. The maximum value of both change in a small range.

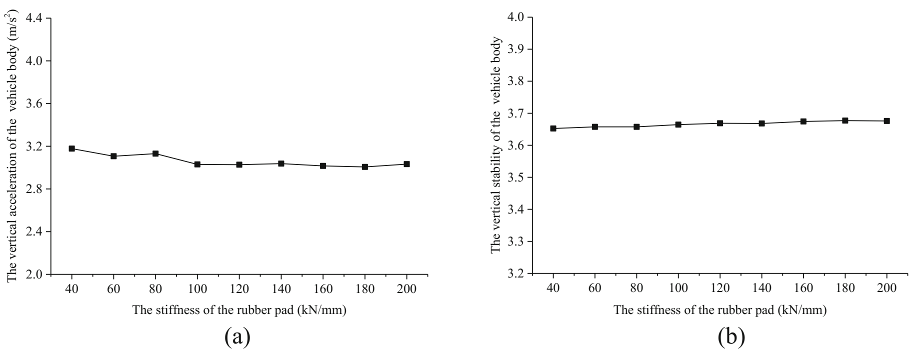

Fig. 5. Influences of the stiffness of the rail pads on the vertical acceleration of the vehicle body

Figure 6 shows that with the stiffness of the rail pads increasing, the maximum value of the lateral vibration acceleration and the stationarity of the car body don't obviously change. The maximum value of the lateral vibration acceleration of the car body varies in the range of 4.36 m/s^2–4.52 m/s^2, and the maximum value of the stationarity of the car body is in the range of 3.58–3.62. So the stiffness of the rail pads has little influences on the lateral vibration acceleration and the stationarity of the car body.

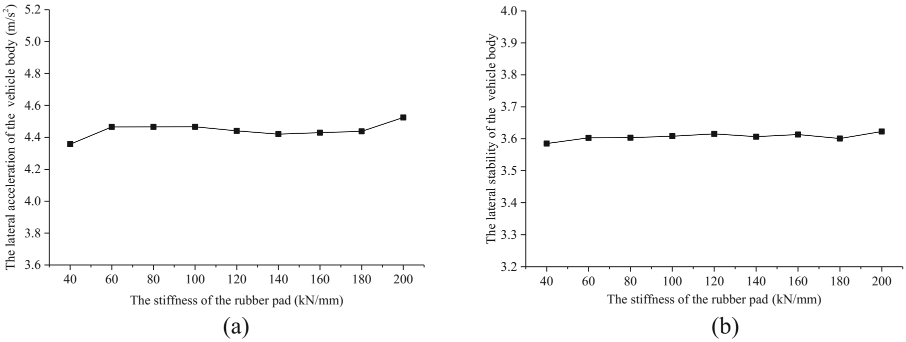

Fig. 6. Influences of the stiffness of the rail pads on the lateral acceleration of the vehicle body

4.2 Influences of the Stiffness of the Rail Pads on Vertical Wheel/Rail Forces

It can be seen from Fig. 7 that with the stiffness of the rail pads increasing, the maximal vertical wheel/rail force gradually stabilized after the initial increase. Figure 7(a) shows the comparison of the vertical wheel/rail force in time-domain when the stiffness of the rail pads are 40 MN/m and 200 MN/m and the maximal values are 214.357 kN and 220.463 kN respectively. Although both are less than the limit value 322 kN, but the vertical wheel/rail force increasing will aggravate the wheel/rail impact and the wheel/rail wear and also will lead to that the sleepers and track bed seriously vibrate and make the track structure vulnerable to damage and even affect the running safety of the wagon vehicle. Therefore, it is favorable that the stiffness of the rail pads is not too high in the heavy haul railway. It should be noted that the stiffness of the rail pads will increase with its aging, so it is need to regularly sample the rail pads and timely replace the aged rail pads.

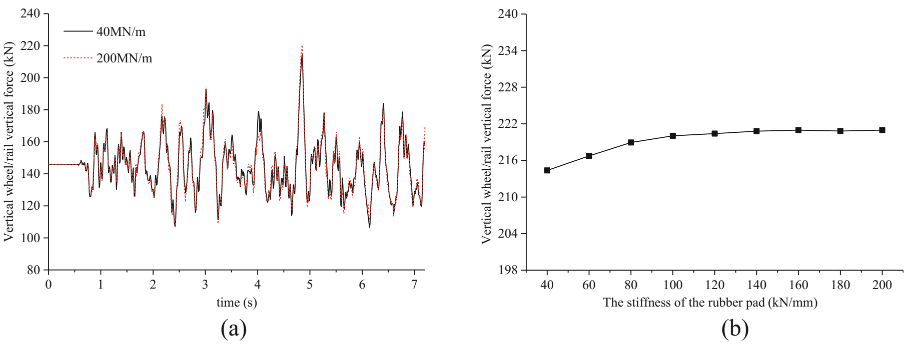

Fig. 7. Influences of the stiffness of the rail pads on vertical wheel/rail forces

4.3 Influences of the Stiffness of the Rail Pads on Lateral Wheel/Rail Forces

According to the field testes of the heavy haul railway in Europe and the United States, the allowable limit value of the lateral wheel/rail force is generally 0.4 times of the axle load [14]. In this paper, the static axle load is 300 kN. So the lateral wheel/rail force should be less than 120 kN. As can be seen from Fig. 8, there was no regular changes of the maximal lateral wheel/rail force with the stiffness of the rail pads increasing. The maximum value fluctuates between 26.67 kN and 31.18 kN, which can meet the safety requirements.

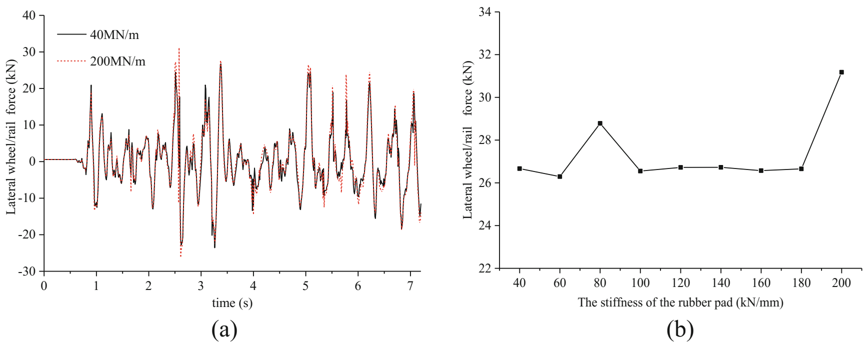

Fig. 8. Influences of the stiffness of the rail pads on lateral wheel/rail forces

The derailment factor is the ratio of the lateral wheel/rail force to the vertical wheel/rail force. According to the standard, *dynamic performance test methods and assessment criteria of railway locomotive* (TB/T2360-93), provides that the derailment coefficient can't be greater than 0.9 [19]. It can be seen from Fig. 9 that the maximal derailment factor fluctuates between 0.188 and 0.220 with the stiffness increase of the

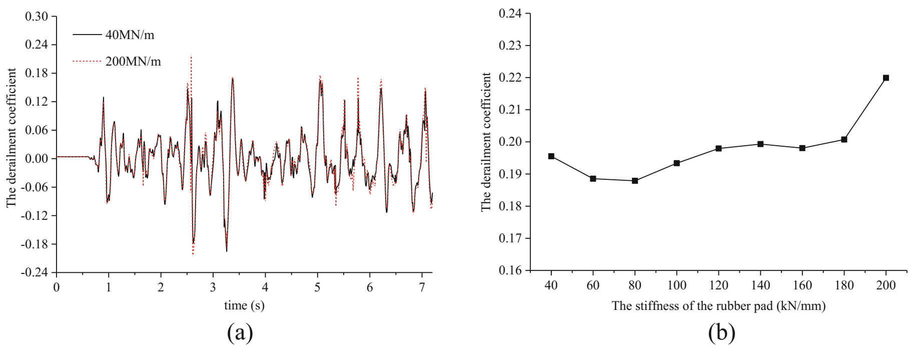

Fig. 9. Influences of the stiffness of the rail pads on derailment factor

rail pads when the vehicle speed is 100 km/h. In general, the fluctuation range of the maximal derailment factor is very small and the overall level is much lower than the limit value. It can be seen that the stiffness of the rail pads has little effect on the derailment factor.

4.4 Influences of the Stiffness of the Rail Pads on Vertical Displacement of Rail

It can be seen from Fig. 10, the stiffness of the rail pads has obvious effects on the vertical displacement of the rail. When the vehicle speed is 100 km/h, the vertical displacement of the rail is greatly reduced with the stiffness increase of the rail pads and the decreasing range becomes smaller. When the pad stiffness is increased from 40 MN/m to 200 MN/m, the vertical displacement of the rail is reduced from 2.070 mm to 0.749 mm and the descend range is 63.8%. Therefore, the vertical displacement of the rail is very sensitive to the stiffness change of the rail pads. For the heavy haul railway, the use of high elastic rail pads will increase the vertical displacement of the rail which is easy to cause the crushing failure of the rail pads and the durability of the rail pads can't be guaranteed resulting in the uneven stiffness of the track structure. Additionally, the vertical displacement of the rail increasing aggravates the vibration of the fastener which is harmful to the life of the fastener and the stability of the connection with the rail and even affects the running safety.

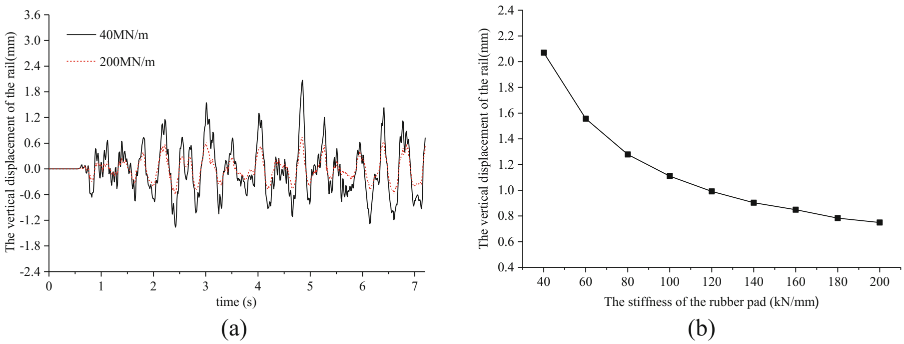

Fig. 10. Influences of the stiffness of the rail pads on vertical displacement of rail

From the above analysis, we can see that the stiffness of the rail pads has a great influence on the vertical displacement of the rail, which can cause many problems. Therefore, the stiffness of the rail pads should be not too low for heavy haul railway.

4.5 Influences of the Stiffness of the Rail Pads on Wheel/Rail Wear

Wheel/rail wear is an important basis for evaluating the running quality of the vehicle and the type of the track. There are rolling friction and sliding friction on the wheel/rail contact surface which will cause the wear of the wheel and rail. The sliding friction between the wheel flange and the rail is an important reason for the side wear of the rail. It can be seen from Fig. 11, wheel/rail wear increases with the stiffness of the rail pads increasing. When the stiffness of the rail pads is increased from 40 MN/m to 200 MN/m, the wheel/rail wear is increased from 0.086 kN/mm to 0.111 kN/mm and the growth rate is 29%. Therefore, the effect of the stiffness of the rail pads on the wheel/rail wear is obvious, reducing the running of the vehicle and the life of the rail.

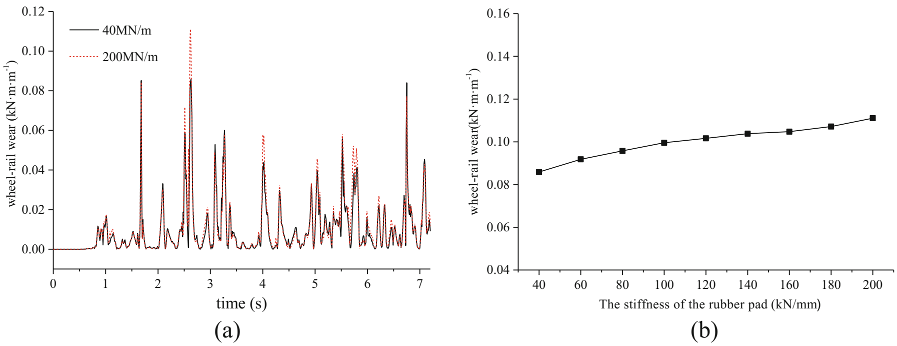

Fig. 11. Influences of the stiffness of the rail pads on wheel/rail wear

5 Conclusions

In most of existing researches, the track structure is often simplified as a single-layer structural model. A composite double-layer dynamic model of the track structure is proposed on the basis of the single-layer structural model in this paper. Then a more practical wagon vehicle-track coupled dynamic model is proposed based on the theory of vehicle-track coupled dynamics. Lastly the wagon vehicle-track coupled dynamic model is used to study the influences of the stiffness of the rail pads on the dynamic performances of the whole heavy haul wagon vehicle-track coupled dynamic system. The results are as follows.

(1) The proposed model is more practical to study the dynamic problems of heavy haul railway and it can analyze the influence of the local structure of the track on the dynamic performance of the whole system.
(2) The primary and secondary suspension system of the wagon vehicle can eliminate the impact of the stiffness change of the rail pads on the dynamic responses of the car body. In the choice of rail pads, the impact of its stiffness on the dynamic response of the car body can be ignored.
(3) The stiffness of the rail pads has obvious effects on the maximal vertical wheel/rail force. For the heavy haul railway, the stiffness of the rail pads should be not too high. Additionally, the stiffness of the rail pads will increase with its aging, so it is need to regularly sample the rail pads and timely replace the aged rail pads. The stiffness of the rail pads has little effects on the lateral wheel/rail force and the

derailment factor which meet the safety requirements. However, the effect of the stiffness of the rail pads on the wheel/rail wear is obvious, reducing the running of the vehicle and the life of the rail.

(4) The stiffness of the rail pads has a great influence on the vertical displacement of the rail, which can cause many problems. Therefore, the stiffness of the rail pads should be not too low for heavy haul railway.

To sum up, it is of great significance for improving the fatigue performance of the elastic rail pads, prolonging the service life of the sleeper, the ballast and the rail and reducing the maintenance and operation cost to reasonably set the stiffness of the rail pads.

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