Field experimental study on the dynamic response of CRTS-I ballastless track subgrade of the Shanghai-Nanjing intercity high-speed railway during operation period

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Abstract. Shanghai-Nanjing intercity high-speed railway, the busiest high-speed rail in China, built with the highest standards, the longest mileages, and the fastest speed among the world. Having been in operation for 5 years, it is important to figure out the performance and rules of dynamic characteristics evolution of the substructure. To study the vibration characteristics of the ballastless track subgrade after a few years of operation, in-situ train-induced tests were carried out in Shanghai-Nanjing intercity railway representative subgrade sections. The value of vertical vibration acceleration, displacement and velocity of different measuring points in both end and center of track slab under the train load is acquired, and distribution regularities of dynamic response for ballastless track subgrade on the period of operation are summarized. The results show that: At the end of track slab, the vibration acceleration value in each layer of the ballastless track subgrade structure decays dramatically in the vertical direction, which appears an exponential trend; while in the center, the vibration acceleration value decays gently in vertical direction, which appears a roughly linear trend. On the position of subgrade surface and road shoulder, vibration acceleration values are closer in both end and center of track slab; The special parts of the end of track slab mainly have an amplification effect on vibration response of the track slab and concrete roadbed, and the train’s speed is considered to have the most notable amplification effect on the vibration acceleration of the end of track slab. The vibration displacements of the track slab and the concrete roadbed show a linear relationship with the variation of the train’s velocity, while this trend is not remarkable on the position of subgrade surface and road shoulder, which is in accordance with the dynamic displacement distribution measured among inner part of the subgrade of high speed railways such as Beijing-Tianjin, Wuhan-Guangzhou, Zhengzhou-Xi'an.

1. Introduction
At the end of December 2019, the total length of China's high-speed railways in operation had exceeded 35,000 kilometers, accounting for more than 60 percent of the world's total length of high-speed railways. The high-speed rail and other railways constitute a rapid passenger transport network that has basically covered cities with a population of more than 500,000. Ballastless track has become the main development direction of high-speed railway track structures due to its characteristics of strong stability, good durability, small plastic deformation and less maintenance [1]. Among them, the slab ballastless track is one of the most widely used and most mature ballastless track structure types.
It consists of steel rails, fasteners, rail plates, the filling cement-emulsified asphalt layer (or CA mortar for short) and concrete base plate. The cement-emulsified asphalt adjusted layer is used as a structural layer between the track slab and the concrete base plate, which mainly plays the role of support, load transmission, vibration reduction, vibration isolation and crack resistance. With the increase of train speed, the size and frequency of the train load on the railway subgrade have changed significantly. It leads to a great change in the dynamic response characteristics of the railway subgrade structure and causes significant dynamic problems.

The vibration response law of subgrade structure of ballastless track under train operation is an important factor that affects the operational safety, comfort property and service life of line infrastructure. The evaluation indicators of the ballastless track-subgrade system dynamic response mainly include the ballastless track dynamic response index and the subgrade dynamic response index. The limiting value of the specified indexes should not only meet the safety and comfort requirements of trains, but also reduce the dynamic interaction in the structures of the ballastless track-subgrade system. At the same time, it can achieve the purpose of prolonging service life and maintenance cycle. Therefore, it is more and more important to study the vibration characteristics of ballastless track subgrade structure when trains are operating. Domestic and foreign scholars have done a lot of research on dynamic response of ballastless track subgrade structure under the impact load of high-speed trains by means of indoor model test, on-site driving test and finite element analysis[2-4].

Dynamic load of high-speed trains is the direct factor that causes the vibration of ballastless track subgrade structure. It is the guarantee of structural design and deformation control of ballastless track subgrade for high-speed railway to define the dynamic stress level and vibrational transmission law of each structural layer of ballastless track subgrade structure system. On-site driving test is the main technical means to reveal the true dynamic action law of ballastless track-subgrade when high-speed train is running. And it is a reliable way to accurately obtain the vibration parameters of ballastless track subgrade. Meanwhile, it is important to evaluate the rationality of theoretical model and dynamic performance [5]. In general, there are few field test studies on dynamic response of ballastless track subgrade. It is limited by objective conditions, so it obtains less data in operation period. In China most of the train speed in dynamic response test of ballastless track subgrade of high-speed railway is not high, which can not reflect the dynamic response of high-speed train.

2. Engineering situation
Shanghai-Nanjing Intercity Railway that is built on soft soil foundation is the first high-speed railway in China. It is a double-track ballastless passenger dedicated line with a speed of 300 km/h. The length of the main line is 300.2km, and the subgrade accounts for 35% of the total length of the line. There are 21 stations along the line, featuring many curves and designing speed limits. CRTS-I slab ballastless track is used in the line, including slab and frame rails. It consists of 60kg/m rail, WJ-7B fastener system, track plate, CA mortar, concrete base plate and convex baffle.

The field test site is the section of the filled embankment, located between a culvert and Xinzhuang Bridge. The subgrade structure is divided into three layers, the surface layer of the foundation bed is 0.4m thick, the bottom layer of the foundation bed is 1.9m thick, and the embankment layer below the foundation bed is 0.6m thick. The form of embankment protection is arch skeleton protection, the distance between upper and lower lines is 4.8m, and one side of the upper line is adjacent to the Beijing-Shanghai high-speed railway. The foundation treatment measures are CFG pile + gravel cushion, the length of the pile is 6–8m, the diameter of the pile is 0.5m, the distance between the piles is 1.6m, square arrangement, and the top of the pile is laid with a double layer geogrid reinforced gravel cushion about 0.6m thick. The section of roadbed structure is shown in figure 1.
3. Field test
Field test site is located in Shanghai-Nanjing intercity downlink, accelerometers, speedometers and displacement meters are placed on the edge of the track slab, the top edge of the base plate, the top surface of the subgrade sealing layer and the shoulder of the road, the components models are CA-YD-117 piezoelectric accelerometer, dynamic piezoelectric displacement gauge, and CS-YD-002M piezoelectric speedometer. Figure 2 is the longitudinal layout of the sensor along the road, and the two sections are arranged at the end of the track plate and the middle of the plate respectively. Data collection is completed by DH5922 dynamic acquisition system.

![Figure 2. The vertical section layout of dynamic test units](image)

The dynamic performance of the vehicle-track-subgrade coupling system under the action of high-speed moving train load is related to the model, speed and direction of the train. The Shanghai-Nanjing intercity trains are mainly composed of CRH2C distributed emu, which consist of 2 trailers (T) and 6 EMUs (M). The formation is T+M+M+M+M+M+M+T. The average axle weight of CRH2C EMU is ≤14t, the length of trailer is 25.7m, the length of EMU is 25m, the bogie center distance is 17.5m, and the fixed wheelbase is 2.5m.

In this test, the effective running number of CRH2C trains of 50, with a speed range of 243km/h-287km/h, which is evenly distributed. Among them, there are 38 trains whose running speed exceeds 260km/h, with an average speed of about 267km/h. The statistics of train running speed are shown in figure 3.
4. Analysis of test results

Vibration is essentially a wave problem, and the essence of the wave is the propagation of energy. A specific wave is three-dimensional, and its three components have different emphasis on different problems. For the vibration caused by the train, the vertical component plays a major role. Therefore, this test mainly tests the vertical vibration response [6].

The coupling effect of the vehicle-track-subgrade system is a more complex dynamic process. As the running speed of the train increases, the dynamic effect between high-speed trains and the line structure will be enhanced, and the strong random vibration characteristics will be shown. Even if the same train passes through the test area at the same speed, the collected response data has a certain degree of discreteness. Therefore, on the basis of the systematic analysis of the test values of 50 trips, this paper takes the speed values of 248km/h, 273km/h, and 287km/h as the representative speeds, and calculates the average value of the peak value of the measured dynamic response when each train passes within the range of 246km/h to 250km/h, 271km/h to 275km/h, and 285km/h-289km/h as the representative test value under three different speeds.

4.1. Vibration acceleration

Vibration acceleration is an important parameter to judge vibration strength, evaluate vibration characteristics and measure structural failure. Excessive vibration acceleration of the unballasted track superstructure seriously affects the comfort and safety of the train. The vibration acceleration of the subgrade reflects the impact of the train on the subgrade, and its magnitude is the main parameter to judge the effect of vibration on the track damage.

In CRTS-I slab unballasted track subgrade space layered structure system, the track slab’s standard length of subgrade section is 4962mm, and the base plate is provided with an expansion joint every 20m. Figure 4 shows the distribution law of vibration acceleration value of unballasted track subgrade at the end and middle of track plate when the train passes at different speed.
Due to vibration energy diffusion and material damping, the dynamic response index values of the unballasted track subgrade layered structure system under the train load are attenuated in the vertical direction. It can be seen from the figure that the vibration response attenuation law of each structural layer of the unballasted track subgrade is different at different longitudinal positions of the track plate. At the end of the slab, the vibration acceleration values of each structural layer of the unballasted track subgrade rapidly attenuated along the vertical direction, showing an exponential trend; at the middle of the slab, the vibration acceleration values of each structural layer of the unballasted track subgrade attenuated vertically along the vertical direction, showing a generally linear trend. When the vehicle speed is 273km/h, at the end of the plate, the average vibration acceleration at the track plate, base plate, subgrade surface and road shoulder is 5.38m/s², 2.19m/s², 0.78m/s² and 0.71m/s², respectively. The ratio is 7.6:3.1:1.1:1.

In the middle of the slab, the average vibration acceleration of the track slab, base plate, subgrade surface and road shoulder position are 1.29m/s², 0.82m/s², 0.60m/s² and 0.55m/s² respectively, and the ratio is 2.3:1.5:1.1:1. It can be seen that the vibration acceleration values of roadbed surface and road shoulder are close to each other in the end and middle of the plate. The vibration response of track plate and base plate is amplified by the special position at the end of the plate.

It can be seen from figure 5 that train operating speed has a significant impact on the vibration response of unballasted track subgrade. In order to further study the relationship between train operating speed and each structural layer of unballasted track subgrade at the end and the middle of the board, the influence law of different train speeds on the vibration response of each structural layer of unballasted track subgrade was plotted (figure 5). In general, the vibration acceleration of each structural layer of unballasted track subgrade has a linear relationship with the speed of train operation. Among them, the vibration acceleration value of the end position of the track plate and the base plate changes greatly with the increase of the train operating speed. When the train passes at 248km/h, 273km/h, and 287km/h respectively, the corresponding vibration acceleration value of the end position Vibration acceleration values of 4.33m/s², 5.38m/s² and 6.83m/s². Compared with the vibration acceleration value of 248km/h, when the train operating speed increases to 273km/h and 287km/h, the vibration acceleration value increases by 24.25% and 57.74%. However, in the middle of the slab, the vibration acceleration value of each structural layer of the unballasted track subgrade is relatively less affected by the train operating speed. As the train operating speed increases, the vibration acceleration value increases gently. Therefore, when the train runs at high speed, attention should be paid to the change of vibration acceleration at the end of the track slab.
Figure 5. Curves of vibration acceleration of ballastless track subgrade structure varying with speed

Table 1. Vibration acceleration of ballastless track subgrade structure in both end and center of track slab under different speeds

| Track slab | Base plate | Surface of subgrade |
|------------|------------|---------------------|
| speed of train/km/h | v=248 | v=273 | v=287 | v=248 | v=273 | v=287 | v=248 | v=273 | v=287 |
| vibration acceleration in end of track slab / m/s² | 1.1 | 1.29 | 1.56 | 0.62 | 0.82 | 1.43 | 0.48 | 0.6 | 1.03 |
| vibration acceleration in end of base plate / m/s² | 4.33 | 5.38 | 6.83 | 1.64 | 2.19 | 2.74 | 0.65 | 0.78 | 1.18 |
| Ratio (track slab end/ track slab center) | 3.94 | 4.17 | 4.38 | 2.65 | 2.67 | 1.92 | 1.35 | 1.3 | 1.15 |

From Table 1, it can be seen that the vibration acceleration value of each structural layer of the unballasted track at the end of the plate is much larger than the position in middle of the plate. The amplification effect on the vibration response of each structural layer of the unballasted track which caused by the end of the plate decreases in the vertical direction, the track slab has the largest influence, the base slab is next, and the subgrade surface has less influence. When the vehicle speed is 248 km/h, the vibration acceleration value of the position at end of the track slab is 3.94 times of the position in the middle of the slab, and as the train operating speed increases, the ratio also increases. When the vehicle speed is 287 km/h, the vibration acceleration value of the position at end of the track slab is 4.38 times of the position in the middle of the slab. The ratio of vibration acceleration of the middle of the base plate to the end of the base plate is less affected by the operating speed of the train, and the variation range is 1.92 ~ 2.67; At the subgrade surface, the vibration acceleration value of the plate end position is slightly higher than that of the plate middle position, and with the increase of the operating speed of the train, the difference between them becomes smaller and smaller. When the speed is 287 km/h, the vibration acceleration value at the end of the plate is 1.15 times of that of the plate middle position. Therefore, it is suggested to pay more attention to the vibration response of the end of the track plate when the service condition of the infrastructure is detected in the engineering section.

4.2. Vibration displacement

Vibration displacement is generated temporarily when the train passes by, and its size depends on factors such as train speed, axle load, line smoothness, subgrade material properties and service status. For the unballasted track, the dynamic displacement reflects the degree of dynamic effect of the train on the unballasted track structure. For the subgrade, the dynamic displacement mainly occurs on the surface of the bed, and the dynamic displacement is finally reflected in the dynamic deformation of the track surface when the train passes, which directly affects the running quality of high-speed trains. High-speed railways operate at high speeds and have high requirements for the smoothness of the lines. The dynamic deformation of the subgrade directly affects the smoothness of the line, and at the same
time, as the main manifestation of the dynamic performance of the bed filler, it can reflect the strain in the bed[7].

In the design code of high-speed railway in China, it is clearly proposed that the thickness of surface layer of subgrade is determined by the principle of deformation and strength control. When the principle of deformation control is adopted, the control condition is that the deformation of the roadbed top surface is no more than 3.5mm under the action of train load. When the deformation modulus of base bed surface $E_1=210$MPa and the deformation modulus of base bed bottom $E_2=34$MPa, the surface thickness of base bed is 70cm, which can meet the control condition of dynamic deformation of subgrade surface $W_0<3.5$. Therefore, the thickness of base bed surface is 0.7m[8]. According to the experience of Japan, when the surface material of the base bed is graded gravel or gravel, the vertical displacement limit of the surface of the base bed is 4mm, and when the surface material of the base bed is reinforced surface structure, the vertical displacement limit of the surface of the base bed is 2.5mm.

Dynamic deformation of roadbed surface under train load is one of the important indexes to evaluate the quality of roadbed filling. For the structural design of high-speed railway base bed, the principle of control is that the filler does not produce plastic cumulative strain under the action of train load. To make the bed work within the elastic range, the dynamic deformation cannot exceed its limit. If the dynamic deformation is too large, it will affect the smoothness of the line and the safety of the train at high speed, and will also cause cumulative plastic deformation of the bed, which will increase the subsidence of the roadbed after construction.

For the subgrade to work within the elastic range, the limit value of dynamic deformation of ballastless track of high-speed railway is 0.22mm. Therefore, the dynamic deformation test of subgrade can provide the basis for judging the quality of subgrade, and also provide reference for the maintenance and maintenance of subgrade in public works department.

Figure 6 is the curve of vibration displacement of each structure layer of ballastless track subgrade with train operating speed during operation period. The dynamic displacement of ballastless track (displacement amplitude and the rate of change along the road) is the basis of driving comfort, stability and guarantee of driving speed. The dynamic displacement is generally determined by track stiffness, which should be controlled in the design, and its essence is the overall stiffness design of the track.

Figure 6 shows that the vibration displacement of the track plate is much larger than that of the base plate and the roadbed surface, which indicates that the vibration energy mainly attenuates between the track plate and the base plate, and further verifies the function of reducing noise and damping of the cement emulsified asphalt mortar layer. Because subgrade shoulder is far away from the vibration source, there is attenuation and superposition in the transverse transmission of vibration.
wave. Therefore, the vibration displacement is close to the roadbed surface. And the mean range of vibration displacement is 0.03-0.09mm.

In general, the vibration displacement of track plate and base plate in ballastless track subgrade structure is approximately linear with the change of train operating speed. When the speed of train operation is low, each structure layer of ballastless track subgrade changes little with the increase of train speed. Among them, the rate of vibration displacement of track plate is higher than that of base plate; when the train operation speed is high and greater than 276 km/h, the vibration displacement increases rapidly with the increase of operating speed. The change rate of vibration displacement of track plate and base plate is close. However, the trend of vibration displacement of subgrade closure and subgrade shoulder with increasing speed is not obvious, which is consistent with the statistical law of big data statistics in high speed rail operation in figure 8.

4.3. Vibration velocity

Vibration velocity is an important dynamic index to study the vibration characteristics of ballastless track subgrade. Figure 7 shows the variation of vibration velocity of each structure layer of ballastless track subgrade with train speed.

![Figure 7. Curves of vibration velocity of ballastless track subgrade structure varying with speed](image)

It can be seen from the figure that the vibration speed at the subgrade surface and subgrade shoulder is less affected by the train operation speed. only when the speed is greater than 280 km/h, it increases slightly with the increase of the train operation speed; The vibration speed of the base plate varies linearly with the train operation speed, and the change rate is flat; The vibration velocity of track plate is close to the vibration acceleration with the overall change trend of train running speed.

5. conclusion

Five years after the opening of Shanghai-Ning inter-city operation, the actual vehicle test was carried out on the typical subgrade section of ballastless track, and the dynamic response distribution law of the subgrade structure of ballastless track at the end and the middle of the plate was analyzed. Based on the results of the test analysis, the following conclusions are drawn:

- The vibration response attenuation law of each structure layer of ballastless track subgrade is different at different longitudinal position of track plate. At the end of the plate, the vibration acceleration value of each structure layer of ballastless track subgrade declines rapidly along the vertical direction and presents an exponential trend. In the middle of the plate, the vibration acceleration of each structural layer of the ballastless track subgrade declines slowly along the vertical direction and shows a roughly linear trend. The vibration acceleration values of subgrade surface and subgrade shoulder are close to each other in the end and middle of the plate. The vibration response of track plate and base plate is amplified by the special position of plate end.
• The vibration acceleration value of each structure layer of ballastless track at the end of plate is much larger than that in plate. The amplification effect of the plate end position on the vibration response of each structure layer of ballastless track decreases along the vertical direction, the influence of track plate is the largest, the base plate is the second, and the influence of roadbed surface is small.

• The vibration displacement of the track plate is much larger than that of the base plate and subgrade surface, which indicates that the vibration energy mainly attenuates between the track plate and the base plate, and further verifies the function of noise reduction and vibration absorption of the cement emulsified asphalt mortar layer. In general, the vibration displacement of track plate and base plate in the ballastless track subgrade structure has a linear relationship with the train operating speed. However, the vibration displacement of subgrade closure and subgrade shoulder does not change significantly with the increase of vehicle speed.

• The vibration speed of subgrade surface and subgrade shoulder is less affected by the operating speed of the train. Only when the vehicle speed is more than 280km/h, it increases slightly with the increase of the operating speed of the train. The vibration speed of the base plate is linear with the change of the train speed, and the change rate is gentle. The overall variation trend of track plate vibration speed with train speed is close to that of vibration acceleration.

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