Study on Vibration Characteristics of Piers and Foundation Sites in Seasonal Frozen Soil Areas under Train Load

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Abstract. In order to study the vibration characteristics of railway piers and different foundation sites in seasonal frozen soil region under train load, the piers and foundation sites of Tieling-Siping of Harbin-Dalian high-speed railway were tested on site, and the vibration attenuation characteristics of different sites and different seasons were analysed using numerical simulation method. The results show that the vibrations in the Y and Z directions are amplified on the side of piled soil-filling in both freezing and non-freezing seasons, when the distance R from the bottom of pier is less than 0.8m. But the vibration is amplified only in Z direction on the side of non-piled soil-filling. In the freezing season or in the non-freezing season, when R is between 1 and 2m, the vibration attenuation speed on the side of piled soil-filling is obviously lower than that on the side of non-piled soil-filling. When R is larger than 3m, the vibration attenuation of three directions is not affected by the piled soil-filling or not. Whether on the side of piled soil-filling or non-piled soil-filling, the vibration attenuation speed in freezing season is lower than that in non-freezing season.

1. Introduction
In recent years, the rapid development of railways has played an increasingly important in the country's economic and social development. According to China railway construction plan, the total length of railway will reach 30,000 km by 2020 in China [1]. Due to the great increase of train speed and load, the vibration problem and the dynamic problem of foundation site become more prominent. Field test and numerical calculation are the two most common and important methods to study train vibration and its site effect. Xia He et al [2] carried out two field tests on the dynamic response of railway bridges, ground and buildings near the railway. Shen Quan et al. [3] analysed the vibration characteristics of a new type of cutting structure under high-speed train loads by numerical simulation and experiments. Dong Liancheng et al. [4] compared and analysed the vibration characteristics of Qinghai-Tibet Railway Subgrade under passenger and freight train loads in permafrost region.

At present, it can be seen that there is little study on the vibration characteristics of railway pier-foundation site in seasonal frozen soil area. In view of this, the pier and the foundation site of Tieling-Siping of Harbin-Dalian high-speed railway are selected as the test section. The acceleration versus time data of pier and different sites are obtained, and the vibration characteristics of the pier and different sites are analysed using numerical simulation. The study is of great scientific significance for qualitative prediction and new design of railway projects in cold regions.
2. Overview of field testing
The site test points are the pier and its foundation site of Tieling-Siping section of Harbin-Dalian high-speed railway. The test site is seasonal frozen soil area. The layout of the site test points of piers and foundation is shown in figure 1.

The instrument selected for this test is the 891-II vibration measurer. The instrument can simultaneously measure acceleration in three directions of X, Y and Z and the sampling interval is 0.005s. The direction of the test section is stipulated as follows: the direction of train operation is X, the direction of vertical train operation is Y, and the vertical direction is Z. Measuring points 1 and 4 are arranged on the foundation site at the bottom of the pier. Because of the accumulation of artificial filling on the right side of the pier bottom, the height of measuring points 1 and 4 is different. The distance of the measuring point 1 and 4 from the bottom of the pier is 0.5m and 0.1m respectively; the measuring points 2 is arranged on the supporting padstone at the top of the pier.

3. Analysis of test results
Taking CRH2C train (running speed is $v=262$km/h, compartment formation is 8) as an example, the acceleration duration curves of measuring points 2 of supporting padstone at the top of pier, and measuring points 1 and 4 of foundation site are shown in figure 2 (the X-direction acceleration versus time data of measuring point 4 cannot be recorded due to the failure of the instrument of measuring point 4 in the testing process). The X-direction peak accelerations of the measured points 1 and 2 are: 27.4cm/s$^2$ and 28.5cm/s$^2$. The Y-direction peak accelerations of the measured points 1, 2, and 4 are: 22.2cm/s$^2$, 26.7cm/s$^2$ and 81.3cm/s$^2$. The Z-direction peak accelerations of the measured points 1, 2, and 4 are: 33.5cm/s$^2$, 23.1cm/s$^2$ and 64.6cm/s$^2$. Obviously, piers and foundation sites have different vibration characteristics under train loads.
4. Effect of different foundation sites on vibration characteristics

4.1. Numerical model
Taking the pier and foundation site of Tieling-Siping section of Harbin-Dalian high-speed railway as the research object, a simplified three-dimensional model is established. The pier height is 10.5m, of which 2m is buried in soil. The size of soil body is 40×40×24m, as shown in figure 3. The model is divided into two parts. The first part is pier, and the pier is embedded in the soil. According to pier construction requirements [5], it can be determined that bored pile is used in this bridge pier. The concrete strength is C30, and the pier is ellipse in cross-section. The pier constitutive model is elastic. The second part is soil, and soil layers from bottom to top are 9m clay, 13m silty clay, 2m yellow silty clay and 1.8m artificial fill. The model of pier and artificial fill is shown in figure 4. The constitutive model of soil is Mohr-Coulomb model. The bottom of the model is fixed boundary, and the left and right boundary are infinite element boundaries in order to reduce the reflection of boundary to vibration wave. The C3D8R element is used for both foundation site and pier. The maximum mesh size of finite element is 2m in the model, which meets the calculation requirements.

According to the geological exploration report of Harbin-Dalian high-speed railway and the construction requirements of the frozen soil area [6], the physical and mechanical parameters of soil can be obtained, as shown in table 1.
4.2. Analysis of calculation results

4.2.1. Vibration attenuation characteristics in non-freezing season

Figure 5 is the relationship curve between peak acceleration $a$ and distance $R$, which is obtained by numerical calculation in non-freezing season. Whether on the side of piled fill or on the side of non-piled fill, it can be seen that the vibration has different site effects in different directions due to the interaction of the soil and the pier at the distance of 0.1m from pier. Compared with the results of actual measuring point 4, vibrations in Y and Z directions are obviously amplified on the side of piled fill. But there is no amplification in X direction. The results of numerical calculation are basically consistent with the actual results of point 4, showing the correctness and feasibility of the established model. At the same time, it can be seen that the vibration attenuation in Y direction is the fastest, followed by Z direction and the slowest in X direction on the side of piled artificial fill when the distance from the bottom of pier $R$ is between 0.1 and 1m. When $R$ is between 1 and 2m, the attenuation speed of the three directions slows down. When $R$ is between 2 and 3m, the attenuation speed of the Y direction and the X direction becomes faster, while the X direction basically remains unchanged. And when $R$ is larger than 3m, the attenuation speed of the three directions slows down dramatically, and the three directions are basically equal.

And on the side of non-piled soil-filling, the vibration is amplified only in the Z direction, but there is no amplification effect in X direction and Y direction. When the distance from the bottom of pier $R$ is between 0.1 and 2m, the vibration attenuates rapidly in Y direction and Z direction. When $R$ is larger than 2m, the attenuation speed is slowed down, and it is basically equal in Y direction and Z direction. However, in X direction, the vibration attenuation speed is faster when $R$ is between 0.1 and 1m, and the vibration attenuation speed becomes slower when $R$ is larger than 1m.

4.2.2. Effect of piled soil-filling or not on vibration attenuation in non-freezing season

Figure 6 shows the influence of piled soil-filling or not on vibration attenuation in different directions in non-freezing season. From the figure, it can be seen that piled soil-filling has a greater impact on vibration in Y and Z directions. The attenuation in all three directions is slower than that in the side of the unstacked soil-filling when $R$ is 0.1–2m. But the vibration only in the Z direction is amplified on

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**Table 1. Physical and mechanical parameters of the soil in the test area.**

| Soil layer          | Density $\rho$/kg/m$^3$ | Elastic modulus $E$/MPa | Poisson's ratio $\nu$ | Cohesion $c$/kPa | Friction angle $\phi$/° |
|---------------------|-------------------------|-------------------------|----------------------|-----------------|-----------------------|
| Frozen | Non-frozen | Frozen | Non-frozen | Frozen | Non-frozen | Frozen | Non-frozen |
| Frozen soil-filling | 1870 | 1870 | 150 | 30 | 0.3 | 0.3 | 35 | 28.5 | 25 | 17 |
| Yellow silty clay | 1900 | 1900 | 160 | 33 | 0.3 | 0.3 | 36 | 29.2 | 25 | 17.1 |
| Silty clay | 1960 | 1960 | 175 | 35 | 0.3 | 0.3 | 37 | 30.5 | 25 | 17.1 |
| Clay | 2000 | 2000 | 200 | 40 | 0.3 | 0.3 | 40 | 30.1 | 30 | 22.1 |

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**Figure 5.** The relationship between of peak acceleration $a$ and distance $R$ in non-freezing season

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**Figure 6.** The relationship between of peak acceleration $a$ and distance $R$ in non-freezing season
the side of the unstacked soil-filling, which is stronger than that of the side of the piled soil-filling. This shows that the vibration characteristics are greatly affected by the piled soil-filling or not beside the pier.

5. Effect of different seasons on vibration characteristics

According to the geological survey report of Hada High-speed Railway, the maximum frozen depth of soil in this area is 2m during the completely frozen season. Therefore, in the numerical calculation, it is assumed that the piled soil-filling and yellow silty clay are in the frozen state, and their mechanical parameters are shown in Table 1.

Figures 7 and 8 are the effects of freezing or not on vibration attenuation respectively. From these figures, it can be seen that, whether there is piled soil-filling or not, the vibration attenuation rate in freezing season is significantly lower than that in non-freezing season. When R is in the range of 0.1-0.4m, vibration in three directions is not affected by freezing on either the side of piled or non-piled soil-filling. When R is in the range of 0.4-3m, the peak acceleration of three directions in the freezing season are obviously larger than those in the non-freezing season. Moreover, the attenuation speed slows down, even the vibration bounces back in the Y and Z directions. However, on the side of non-piled soil-filling, the X-direction vibration is little affected by the freezing, and basically coincides with the non-freezing season. And the peak acceleration in the Y and Z directions is larger than that in the non-freezing season.

6. Conclusion

By choosing pier and foundation site of Tieling-Siping section of Harbin-Dalian high-speed railway as
the test site, the vibration acceleration time histories of the supporting padstone of top pier and different foundation sites are tested under the train load, and the vibration attenuation characteristics of different sites in seasonal frozen soil area are analyzed using numerical simulation methods. The main conclusions are as follows:

1) Vibration characteristics of piers and foundation sites are different. When the distance R from the bottom of pier is less than 0.8m, the vibration in different directions shows different characteristics on different sites. And the Y and Z directions vibration are amplified on the piled soil-filling. But the vibration in only the Z direction is amplified on the non-piled soil-filling.

2) Due to the influence of piled soil-filling, when R is between 1 and 2m, the vibration attenuation speed of piled soil-filling is obviously lower than that of non-piled soil-filling in both freezing and non-freezing seasons.

3) In the freezing season, because the soil is frozen, the stiffness of the soil is increased, and the wave transmission speed is fast. And the vibration attenuation speed is less than that in the non-freezing season, whether on the side of piled soil-filling or on the side of the non-piled soil-filling.

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