Numerical Analysis and Tests on Vibration Reduction Effects of a New Vibration Isolation Module

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Abstract

The vibration reduction effects of a new vibration module which was composed of double-layer tubular structures and the middle filling material were investigated with the methods of numerical simulation and experiment. The attenuation decibels of the vibration levels were measured and analyzed under various working conditions. It is testified that results of numerical simulation of the soil vibration which are in good agreement with the measured data are credible. It is indicated by the analysis results that the vibration isolation module has good effect on damping vibration in each frequency band. The results can provide references for the design of vibration isolation modules for pier foundation.

Keywords: Vibration isolation module; vibration; vibration isolation; FEM; experiment; vibration level

1. Introduction

With the development of urbanization and advancement of people’s living standard, impacts on surrounding environment made by the vibration which is induced by the running trains are causing the reaction with so strong community. Academics and engineers across the world seek for various effective isolation measures. This paper presents the new-type vibration isolation module proposed by author, which is composed of double-layer tubular structures and the middle filling material. It is suitable for vibration suppression and isolation of environmental vibration caused by the elevated rail transit, which

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has better stability, lesser construction areas (within the limits of a 6 meters circle from the center of the bridge pier) and less effect on surroundings. The vibration isolation module encompasses pier footings of the viaduct bridge. The energy of vibration wave gradually reduces, which passes through the first barrier, then enters into the filling stratum, and finally gets through the second barrier, thereby attains the aim of vibration alleviation.

In this paper, firstly, the vibration reduction effects of a new vibration isolation module was investigated by experiments and the three dimensional finite element method with the ANSYS software which was adopted to simulate the ground vibration of around the new vibration isolation module, then the computed results were compared with the measured values and the experiment results demonstrate that the model was correct. Finally, the mitigation effects of the vibration isolation module were evaluated.

2. Experiments of the Vibration Isolation Module

A set of SPC-51 vibration analyzer and five VSE-15-D1 servo sensors made in Japan were adopted in the experiment. The 1 m high vibration isolation module under the ground surface was made up of the 240mm thick inner cycle brick masonry, 520mm thick ditch or filler material layer and the 240mm thick external cycle brick masonry which was constructed with MU10 sintered shale brick and M2.5 cement mortar in the experiment. Isolation ditch was around 1.4-2m thick which was dug before the inner brick masonry was built, and sand or gravel with a diameter of 10 millimeter was used as the filler material. The inner ring radius of the inner cycle brick masonry was 3m and one of the outer ring brick masonry was 4m.

That the 2kg shot in air 2.05m above ground fell freely toward the center of a circle of the vibration isolation module from rest was as an exciting force. There were the 1st-5th measuring points, which were located at 2.5m, 4.5m, 7.5m, 11m, and 15 m away from the center of a circle of the vibration isolation module, respectively. Vertical, radial horizontal and tangential horizontal accelerations of each measurement point under 6 working conditions were measured at the same time. Case 1-6 were no vibration isolation, isolation ditch, inner cycle brick masonry, and inner cycle brick masonry-ditch-external cycle brick masonry, inner cycle brick masonry-layer of sand-external cycle brick masonry and inner cycle brick masonry-layer of gravel-external cycle brick masonry, respectively.

3. Numerical simulation

3.1. Model descriptions

Table 1. Soil properties

| Soil layer | Soil type     | Thickness (m) | Depth (m) | Unit weight (kg/m³) | Compression modulus (MPa) |
|------------|---------------|---------------|-----------|---------------------|---------------------------|
| 1          | Miscellaneous fill | 0.5           | 0.5       | 1890                | 2.0                       |
| 2          | Silt clay     | 2             | 2.5       | 1670                | 3.0                       |
| 3          | Gray clay     | 7.5           | 10        | 1840                | 5.0                       |
| 4.         | Tawny clay    | 10            | 20        | 1941                | 10.0                      |

Theoretically, the three-dimensional space model is the most close to the true state of the structure, and the calculation accuracy is higher. In this paper, the three-dimensional finite element calculation model of the soil vibration around the vibration isolation module was established by Ansys three-dimensional FEM program. In this program, the soil and the vibration isolation module were simulated by three-dimensional solid elements (solid45). Material parameters of the soil are shown in Table 1. The soil boundary must be
set to an artificial boundary in order to avoid calculation distortion caused by wave reflection on model boundary. Referring to the reference [1], 3D consistent viscous-spring artificial boundary and viscous-spring boundary element have been adopted in this paper.

Based on the Hertz’s elastic impact theory, the maximal impact force of the shot falling freely from the references [2] and [3] can be computed by the following equation (1).

\[ F_{\text{max}} = 1.767 \times \rho^{-1/5} \times m^{2/3} \times \left\{ E / (1-\mu^2) \right\}^{2/5} \times (g \times H)^{3/5} \]  

(1)

Where \( F_{\text{max}} \) represents the maximal impact force of the shot; \( \rho \) and \( m \) represent the density and quality of the shot respectively; \( E \) and \( \mu \) is elastic modulus and Poisson ratio of soil, and \( H \) is the height of the shot falling freely, \( H = 2.05 \text{m} \) in this paper.

The impact time \( \Delta t \) of the driven shot to attack the ground in the reference [4] which is well coincident with the practical result can be generally expressed as follows

\[ \Delta t = (1/100) \times (0.097 \times m \times g + 2.21 \times h + 0.045/H + 1.2) \]  

(2)

Where \( h \) is the thickness of buffer soil layer, \( h = 0 \) in the article.

Referring to the reference [4], [5] and [6], the curve of the wallop followed time was an approximate semi-sine wave. Thus, the impact of change with time is assumed as follows

\[ F(t) = F_{\text{max}} \times \sin\left(\frac{\pi}{\Delta t} \times t\right) \]  

(3)

3.2. Model reliability

The attenuation curve of the vertical acceleration vibration level for case 1 by linear regression and curve simulation in the study can be expressed as

\[ VL_z = 66.81 - 18.43 \times \log_{10} R^{0.5} \]  

(4)

Fig.1. The FEA model (a)

Fig.2. Curve of vertical vibration level (b)

The simplified model in Figure 1 was put forward to calculate the test model, of which results were used to contrast with test results in order to verify the reliability of the rectified model. The calculated results and the measured data are as illustrated in Figure 2. Tendencies of variation laws of the attenuation curve between the numerical simulation and the actual measurement are uniform from Figure 2. Considering the error in the complexity of the experimental site and the numerical simulation model predigestion, it can be considered that the FEA model is proved to be effective, which provides the base for the calculation of vibration reduction effects of the vibration isolation module.

4. Result and analysis
4.1. Acceleration vibration level

The measured and calculation vibration levels of each measuring point under every working condition in three directions are shown in Figure 3. The laws of the measured and calculation vibration level attenuation are consistent in general. It can be seen from Figure 3 that the vertical vibration levels are significantly greater than the horizontal vibration levels of the same point for each case. The mitigation of the vertical vibration levels is larger than that of the horizontal vibration levels. Therefore the vertical vibration is primary under every working condition. The vertical vibration levels of the 2-5 points were reduced by 4.01dB, 5.7dB, 3.98dB and 3.15dB respectively in Figure 3. The measured results suggest that the mitigation effect of isolation ditch is optimal, and the inner cycle brick masonry-ditch-external cycle brick masonry takes the second place, and the inner cycle brick masonry-layer of sand-external cycle brick masonry is the third, then is the inner cycle brick masonry-layer of gravel-external cycle brick masonry, and the inner cycle brick masonry is worst.

4.2. Vibration levels in one-third octave band centre frequency

The vertical vibration levels in one-third octave band centre frequency of each measuring point for case 5 are shown in Figure 4. The test results indicate that with the increase of distance, the vertical vibration level of high-frequency decreases quickly. The vibration of 1-80Hz frequency components has been the biggest influence on the body in environment vibration. In reference [7], the vibration frequency at 10 m from the viaduct consists of three main parts: low frequency (about 6.3Hz), middle frequency (around 20Hz) and high frequency (approximately 50-63Hz). Figure 5 shows the vertical vibration level reduction effectiveness analysis in one-third octave band centre frequency at the test point 3 under various working conditions. Vibration reduction effects of the vibration isolation modules are different in different frequency. The vertical vibration levels of the point 3 for case 2 reduce when the frequency range is higher than 16Hz. However, the phenomenon that the vertical vibration levels rebound to increase happens in frequency components of 4Hz-12.5Hz. The mitigation of the vibration of the point 3 for case 5 are better in different frequency
considering construction and maintenance convenient, reliable operation and so on.

![Graph](image1)

![Graph](image2)

Fig.4. The vertical vibration level in one-third octave band centre frequency of each measuring point for case 5  (a)
Fig.5. The vertical vibration level in one-third octave band centre frequency at the 3rd measuring points  (b)

5. Conclusion

Based on the test and calculation results, the following conclusions may be made

(1) The amplitude of the vertical acceleration is gradually reduced with the increase of the distance. The high-frequency vibration mitigates faster than the lower-frequency vibration.

(2) The vertical vibration levels are significantly greater than the horizontal vibration levels of the same point for each case and the vertical vibration is primary under every working condition.

(3) The inner cycle brick masonry-layer of sand-external cycle brick masonry has better effect on damping vibration in each frequency band considering construction and maintenance convenient, reliable operation and so on.

The results can be taken as references for the design of vibration isolation modules for pier foundations of viaduct.

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References

[1] Gu Yin, Liu Jingbo, Du Yixin. 3D consistent viscous-spring artificial boundary and viscous-spring boundar element[J]. Engineering Mechanics, 2007, 24(12): 31-37. China academy of railway science. The numerical study on the vibration and noise of ballastless track in high-speed railway. Beijing. 2007.

[2] Bai Bing. A study on the impact force of pounder[J]. Under Ground Space, 2000, (02): 92-95.

[3] Jing Hongyuan, Analysis and numerical simulation on dynamic response of buried pipeline caused by rockfall impaction[D]. Wuhan: China University of Geoseienees. 2007.

[4] Yang Qixin, Guan Baoshu. Test and research on calculation method of falling stone impulsive force[J]. Journal of the China Rail Way Society, 1996, 18(1): 101-106.

[5] Hoppmann, W. H. Impact on a multispan beam[J]. J. Appl. Mech., Trans. ASME, 1950, (72): 409-414.

[6] Gai Bingzheng, Zheng Zhiqiang. Analytical investigation of contract force in a rectangular plate is impacted by a sphere[J]. Journal of Vibration and Shock, 1990, 2: 14-21.

[7] Zhang Xin. Practical and the oretical research on the environmental vibration caused by elevated railroad traffic[D]. Shanghai: Tongji University, 2002.