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Characteristics of Vibration Sources and Their Propagation Properties in Shield Construction

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

The vibration generated during the shield construction process may have an impact on the surrounding environment and structures, so it is particularly important to study the characteristics of its vibration sources and propagation properties. This paper analyzes the characteristics of the main vibration sources of the shield machine during the construction process, including the vibration frequency, amplitude distribution and so on. Through the literature research of various experts and scholars, the change rule of vibration sources under different working conditions is explored, and the propagation characteristics of vibration in the soil body are studied. This study can provide reference basis for vibration control and environmental protection during shield construction. The main conclusions are as follows: 1) the vibration during shield construction is mainly generated by the interaction between the cutter plate and the surrounding rock; 2) the frequency of vibration caused by shield construction is mainly in the range of 0~80Hz, and the

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amplitude is related to the nature of the excavated soil and the construction parameters; 3) the vibration tends to decrease with the increase of the distance, and the high-frequency vibration propagates faster than the low-frequency attenuation in the soil body.

Keywords: Shield tunnels; construction vibration; vibration propagation.

1. INTRODUCTION

In recent years, China's urbanization is developing very rapidly, in order to solve the problem of urban traffic congestion, subway transportation has become one of the main ways of national travel. Nowadays, many first-tier cities in China have built a perfect subway network, and second-tier cities are also putting into a new round of subway construction. Among various underground engineering construction techniques, shield method is a construction technique suitable for tunnel construction, which has been widely used in urban rail transit projects [1]. However, shield construction also brings us some new technical problems, among which the vibration of surrounding rock caused by shield method construction is one point that needs to be emphasized.

When tunneling by the shield method, a certain degree of construction vibration phenomenon is generated. The planned routes of urban underground tunnels often pass through densely populated and built-up busy areas, which inevitably leads to construction areas adjacent to or even directly through some important buildings, especially sensitive structures including ancient cultural relics buildings. For example, the Xi'an subway crosses the ancient city center [2], where several tunnels pass underneath ancient city walls [3].

Shield method of construction vibration caused by the surrounding rock vibration source has a variety of factors, in the construction process, the cutter plate cutting soil, shield machine itself, the operation of construction vehicles and other reasons will trigger the construction of vibration, through the soil around the tunnel to the outside world, will have an impact on the surrounding buildings [4]. In the process of shield construction digging, if vibration with large amplitude and low frequency occurs, it may cause damage to the surface building and cause uneven settlement and other hazards. Although the vibration induced by the shield construction method is smaller compared to the vibration effect on the surrounding rock induced by construction methods such as drilling and blasting, it is not negligible. If the vibration exceeds the permissible magnitude, it will have an adverse effect on nearby buildings [5]. At present, most studies focus on the effects of vibration on buildings during the operational phase of tunnels [6,7], and there is relatively little research on the vibration of shield construction, this paper will summarize the sources of vibration of the surrounding rock caused by shield construction and summarize the characteristics of the sources of vibration of shield construction through the existing literature.

2. SOURCES OF VIBRATION IN SHIELD CONSTRUCTION

Vibration is an unavoidable phenomenon during shield tunnel construction. The source of this vibration is mainly generated by the operation of construction equipment, especially the advancement of the shield machine, cutting, grouting and other operational processes, which are the key links to trigger vibration. Specifically the vibration source includes the following parts [8,9,10]:

1) Shield cutterhead: The shield cutterhead is the core part of the shield machine, and its main function is to cut the rock and soil. The cutterhead contacts with the rock and soil while rotating, which generates huge shear and compressive stresses. These forces cause vibrations in the formation, especially when cutting hard rock, pebble layers or mixed formations. In addition, the cutterhead will be subjected to uneven forces in the formation during cutting, and these forces will be transmitted to the overall structure of the shield machine, causing vibration.

2) Propulsion system: The propulsion system of a shield machine usually consists of several hydraulic cylinders and hydraulic pumps. The propulsion system applies thrust in the forward direction of the shield machine through the cylinders to push it forward. Due to the non-homogeneous nature of the ground and variations in geological conditions, the propulsion force is often not uniform, which can lead to vibrations in the propulsion system. In addition, pressure fluctuations and pulsations in the flow of hydraulic fluid generated by the hydraulic system during operation are also important sources of vibration. The vibration of the propulsion system will be more obvious especially in the case of rapid propulsion or encountering high resistance.

3) Discharge system: The soil discharging system is responsible for conveying the cut down soil to the rear of the shield machine, and usually adopts screw conveyor or belt conveyor for soil conveying. During the operation of screw conveyor, due to the friction and collision between the screw blades and the soil, it will produce large vibration. At the same time, the frictional resistance and the change of friction force that the soil body is subjected to during the conveying process will also cause vibration. In addition, when the soil body is discharged from the shield machine and then enters the soil silo or soil truck, the fall and collision of the soil body will generate shock vibration.

4) Lining assembly system: During the advancement of the shield machine, the tunnel lining needs to be assembled. The lining assembly system usually consists of assembling machine and assembling ring. During the assembly process, handling, docking and installation of the lining rings will generate mechanical vibration, especially in the docking process of the lining rings, due to docking errors and collision will generate large shock vibration. In addition, the uneven force and reaction force during lining assembly will also cause system vibration.

5) Auxiliary equipment: Various auxiliary equipment is also used in the shield construction process, such as grouting system, ventilation system, drainage system and so on. This auxiliary equipment will also produce different degrees of vibration during operation. For example, the grouting system will produce pulsating vibration due to the high-pressure injection and flow of the slurry during grouting; the fans and pipes of the ventilation system will produce noise and vibration of air flow during operation; and the drainage system will also cause vibration and noise of the water flow during water pumping and drainage.

6) Friction between shield shell and ground layer: The friction between the shield machine's shell and the surrounding strata during its advancement is also an important source of vibration. Especially in the case of complex ground conditions or high friction, the friction between the shield shell and the ground layer can cause significant vibration. In addition, when the shield machine encounters obstacles in the strata or hard rock layers, the shield shell will be subjected to a greater reaction force, thus causing severe vibration and impact.

3. SHIELD CONSTRUCTION VIBRATION CHARACTERISTICS

Factors such as the weight and stiffness of the shield machine, the setting of the digging parameters, and changes in soil conditions can have a significant impact on the magnitude and frequency distribution of vibration. The types of data for detecting vibration caused by shield construction are mainly divided into frequency and amplitude of vibration, and the following will be carried out to characterize the vibration of shield construction from these two aspects.

3.1 Characteristic Frequencies

The vibration frequency generated during shield construction has complex characteristics with a wide range of frequencies, mainly concentrated in the 0-80 Hz band. Vibration frequency is one of the important parameters for evaluating the impact of vibration, and vibration of different frequencies has different impacts on the environment and buildings.

Specifically, in the process of shield construction, the most important source of vibration is generated by the interaction between the shield cutter plate and the soil at the palm surface. Guo Fei et al. [11] through on-site monitoring of vibration caused by shield construction in the sandy pebble subgrade of Lanzhou obtained the acceleration time curve of soil vibration in the vicinity of the shield cutter and analyzed it, and the results showed that the high-frequency part of the shield construction vibration was rapidly decaying, and the vibration frequency of the ground surface was mainly dominated by 12.5-80Hz. Tao Lianjin et al. [12] carried out on-site vibration monitoring for the shield construction section of a subway in Lanzhou and found that the vibration frequency transmitted to the ground surface was mainly concentrated in the range of 0-80Hz. Tao Lianjin et al. conducted on-site vibration monitoring of a shield construction section of Lanzhou subway, and found that the vibration caused by construction was mainly concentrated in the frequency between 0 and 80 Hz. Wang Xin et al. [13] conducted on-site testing of the vibration response of the surrounding environment caused by shield construction in the shield construction section of a subway tunnel in Beijing as an engineering project, and the data showed that the main frequency distribution of the vibration source of the shield construction was from 5 to 45 Hz, and proposed that the main construction parameters affecting vibration were the torque of the cutter plate the total thrust of the shield machine, and so on.

In summary, the vibration frequency of shield construction is mainly distributed between 0 and 80 Hz, in which the low-frequency vibration spreads farther, and the low-frequency vibration is caused by the propulsion of the shield machine, the rotation of the cutter disk to break the rock, and the operation of the screw conveyor and other large-scale mechanical components. These components produce periodic motion in the working process. Therefore, the factors affecting low-frequency vibration during shield construction are mainly the design of the cutter disk, the degree of wear of the tool, the hardness of the soil or rock, the propulsion speed, and the design of the conveyor. Low-frequency vibration spreads farther and has a greater impact on the surrounding buildings and infrastructure, which can easily cause resonance of the buildings and lead to structural damage or foundation settlement. High-frequency vibration propagation distance is closer, and its causes are mainly the operation of the motor, high-speed rotating parts, the operation of the mechanical transmission system. Therefore, the factors affecting high-frequency vibration are mainly the power of the motor, rotational speed, load conditions, and the wear and tear of the internal parts of the motor, the design of the transmission system, the dimensions and mesh accuracy of the gears, and the tensioning degree of the conveyor belt.

3.2 Amplitude Characterization

During the shield construction process, the amplitude size is mainly related to the shield construction parameters, (including the type of surrounding rock, shield machine digging speed and other factors). Zhu et al. [14] established the relationship between the vibration amplitude of the shield machine body and the influencing factors by using multiple linear regression through on-site testing of the soft soil subgrade and the upper-soft and lower-hard strata. i.e.,

$$\mathrm{Y} = \mathrm{b}_0 + \mathrm{b}_1\mathrm{X}_1 + \mathrm{b}_2\mathrm{X}_2 + \mathrm{b}_3\mathrm{X}_3 + \mathrm{b}_4\mathrm{X}_4 + \mathrm{b}_5\mathrm{X}_5 + \mathrm{b}_6\mathrm{X}_6 \quad (1)$$

where: Y is the dependent variable (vertical vibration velocity at typical measurement points), b_0~b_6 are the partial regression coefficients, and X_1 ~ X_6 are the average dynamic elasticity modulus of the palm surface, the shield machine digging speed, the torque, the total thrust, the rotational speed, and the depth of burial of the influencing factors, respectively.

Wang Xin et al. [15] took the shield construction section of Beijing Metro Line 8 as the engineering Beijing, the data obtained from on-site monitoring were analyzed, and the initial term formula of environmental vibration caused by shield construction was proposed:

$$\mathrm{V}_0 = \mathrm{a}_0(\mathrm{E}_{\mathrm{dw}} + \mathrm{a}_1\mathrm{E}_{\mathrm{df}})^{\mathrm{b}\ln \mathrm{F} + \mathrm{c}\ln \mathrm{T}} \quad (2)$$

where: V_0 is the initial term of environmental vibration caused by shield construction (mm/s); E_{dw} is the weighted dynamic elastic modulus of the soil layer at the excavation surface (MPa); E_{df} is the weighted dynamic elastic modulus of the soil layer, F is the total thrust of the shield machine (MN); T is the torque of the blade of the shield machine (MN-m); a_0 is the overall influence coefficient of the dynamic elastic modulus of the soil, a_1 is the additional influence coefficient of the dynamic elastic modulus of the overburden soil, b and c are the influence coefficients of total shield thrust and cutter torque, respectively.

From Eqns (1) & (2), it can be seen that the factors affecting the amplitude of shield construction are mainly the weighted dynamic elastic modulus of the soil layer, the total thrust of the shield machine, the torque of the cutter plate, and the digging speed of the shield construction, etc. The comprehensive study shows that the dynamic elastic modulus of the working surface of the shield machine is the main factor affecting the amplitude.

4. VIBRATION PROPAGATION CHARACTERISTICS

The propagation of vibration in subway tunnels is mainly divided into two periods, one is the vibration caused by the construction period, and the other is the vibration caused by the operation period. For the construction period, most of the research focuses on the environmental vibration propagation caused by drilling and blasting method and other construction methods, and less research on the propagation of vibration in the surrounding rock medium caused by shield method construction. For the operation period, mostly focused on the study of vibration propagation caused by subway operation.

Zhang Xinshang et al. [16] through the combination of numerical simulation and field test method, studied the mechanized construction tunnel blasting vibration distribution in the surrounding rock, numerical simulation results are basically in line with the measured data, along the radial direction of the tunnel blasting vibration impact of the larger range of 0 ~ 6 m.

Huang Qiang et al. [17] took Shanghai Metro Line 9 as the research background, acceleration sensors are arranged in the tunnel, the surrounding soil layer and various parts of the surface, and the vibration caused by the subway operation is tested in the field, and the propagation law of the subway vibration is analyzed, and the results show that the direction of subway vibration is dominated by pendant vibration, and the vibration level increases when it transmits from the tunnel to the surface via the soil layer, which may be related to the reflection of the boundary plane of the ground surface and the acceleration amplification zone is 20~30 m away from the center of tunnel. The range of 20-30 m from the center of the tunnel is the acceleration amplification area.

Gupta et al. [18] took the key parameters that have a significant effect on the generation and propagation of vibrations in underground railroads and were analyzed through a parametric study, which showed that material damping and shear modulus of the soil have a significant effect on the propagation of vibrations, i.e., the vibration level is higher when the tunnel is in softer soils but the propagation attenuation is greater, resulting in comparable levels of vertical vibration in softer and stiffer soils at a greater distance from the tunnel.

In order to examine the law of vibration propagation in the ground surface, the field vibration test is carried out by Wang Futong et al. [19] with the Beijing Urban Railway Line 13 as the research background, and the test data are analyzed, and the results show that the vibration at the near track is dominated by the high frequency, and the vibration away from the track is dominated by the low frequency, and the vibration level of the frequency bands does not show monotonous attenuation with the increase of distance, and the rebound phenomena occurring in the frequency bands which are close to the superior frequency of the soil layer are larger.

Using ANSYS finite element software, Wang Liming et al. [20] selected representative subway tunnels of different soil layers, rock layer characteristics of numerical simulation, and studied the surface vibration response caused by subway train operation in different tunnel media, the results show that the subway vibration response within the range of 50 m is not much difference.

Using numerical simulation method and the first interval of Beijing Subway Line 16 as the engineering background, the impact of vibration generated during the operation of the subway on the vibration of surface buildings is studied by Liu Li et al. [21] and vibration damping measures are given. They showed that: adopting the floating plate roadbed track has a better effect of vibration control on the buildings, which can meet the normal use of high-rise buildings on the surface.

When the vibration caused by shield construction propagates in the surrounding rock, the low-frequency vibration attenuation is slow and the high-frequency vibration attenuation is fast, which is similar to the propagation of vibration caused by underground transportation and earthquake [22]. The attenuation characteristics during vibration propagation are determined by geometric damping and material damping. Geometric damping is related to the location and type of vibration source, and it describes the phenomenon that the energy density of vibration spreads and decreases as the propagation distance increases. Material damping, on the other hand, is related to the properties of the propagation medium, such as the internal friction of the soil, which absorbs the vibration energy and leads to a gradual decrease in amplitude [23]. The study by Kim et al. [24] showed, through analysis of field monitoring data, that measured vibration attenuation data were more consistent with predicted results when using geometric damping coefficients, suggesting that geometric damping plays a dominant role in vibration attenuation in a given situation.

5. SHIELD CONSTRUCTION VIBRATION CONTROL METHODS

To protect neighboring buildings from irreversible effects of vibration, vibration control means are usually used to mitigate the hazards caused by construction vibration. Combined with the generation principle and propagation characteristics of vibration during shield construction, vibration isolation and damping measures can be considered from two aspects: vibration source and vibration propagation path.

5.1 Vibration Source Control

Optimize the shield tool structure. The tool on the cutter plate is in direct contact with the complex geotechnical environment and is subjected to high intensity impact loads. Different forms of cutter structure result in different vibrations when cutting geotechnical bodies. Huo et al. [25] established a multi-degree-of-freedom coupled dynamics model by using the concentrated mass method to numerically simulate and analyze the cutter tool and optimize the local structure of the tool. Subsequently, the design scheme was verified by tool vibration tests. The results show that the optimized structural system can effectively reduce the vibration generated during the tunneling construction and reduce the wear of the cutter tool.

The MRE isolator has the characteristics of fast response speed, wide range of operating frequency, and simple control parameters, and has been widely used in the field of industrial vibration control. [26,27]. Yang et al. [28] applied the magnetorheological vibration isolator to the vibration reduction of shield tunneling machine, and established a dynamic nonlinear model of tunneling machine including magnetorheological vibration isolator by using the concentrated mass method. The simulation results show that the vibration generated by shield construction can be reduced by 22.51% after the installation of controllable magnetorheological vibration isolators.

5.2 Control of Transmission Routes

Soil is the direct medium of vibration propagation. Cutting off the vibration propagation pathway can also be effective in reducing the impact of vibration on neighboring buildings. The effectiveness of vibration isolation trenches for empty and filled trenches depends mainly on the ratio of the trench depth to the wavelength of the surface wave. Yuan et al. [29] used 2.5-dimensional finite element method to establish the analytical model of trench vibration isolation, and studied the performance of trench vibration isolation under different foundations and the influencing factors. The study shows that the deeper the trench is, the stronger the vibration wave isolation effect is and the better the vibration isolation effect is. Cai et al. [30], Leung et al [31] studied the vibration isolation effect of concrete filler trench, and analyzed the effects of trench width, depth and different tunnel depths on the vibration isolation effect of filler trench. Ulgen et al. [32] compared the vibration isolation performance of hollow trench, water-laden hollow trench and foam-filled trench, and the results showed that the vibration damping capacity of foam-filled trench, hollow trench and water-laden hollow trench decreased in order. Other scholars have verified the vibration isolation effect of geofoam through field tests, and its vibration reduction effect can reach more than 68%. [33,34]. Wave Interceptor Blocks (WIB) are designed for low-frequency vibrations generated by train operation [35]. Takemiya [36] used a new type of honeycomb wave block in the construction of Taiwan's Shinkansen, which is filled with vibration-absorbing materials in the honeycomb pores of the block to significantly absorb vibration energy and reduce vibration levels. Damping hole technology has been widely used in drilling and blasting method of tunnel excavation damping [37,38], the blasting generated by the different frequencies of the three kinds of waves (shock waves, stress waves, seismic waves) have a good reduction effect. Vibration damping holes on the body wave weakening principle is to block and absorb the body wave energy through the vibration damping tube, through the vibration damping tube, the greater the wave energy attenuation effect is obvious. Huang [39] through the control of the rotational speed of the cutter plate, bentonite mixing grouting, playing a vibration damping hole three methods of vibration damping effect research, the results show that playing a vibration damping hole vibration damping effect is the best, the average vibration speed peak reduction of 38.4%.

6. CONCLUSION

1) During shield construction, vibration is mainly generated by the interaction between the cutter plate and the surrounding rock;
2) The vibration frequency caused by shield construction is mainly concentrated in the range of 0~80Hz, and the amplitude is affected by the nature of excavated soil and construction parameters;
3) The vibration is gradually weakened with the increase of distance, and the propagation of

high-frequency vibration in the soil body attenuates faster than low-frequency vibration.

4) By optimizing the tool structure, applying magnetorheological vibration isolators and drilling vibration-damping holes, shield construction vibration can be effectively reduced, thus reducing environmental interference.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

I hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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