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# Study on highway dynamic load vibration propagation characteristics in surrounding soil and influence control distance

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**Abstract:** The dynamic monitoring for the scene of the engineering vehicle dynamic load of the vibration was performed. By developing a subroutine of ABAQUS DLOAD to simulate the process of vehicle traffic, the characteristics of vehicle vibration transmission in soil was analyzed. Based on three different indicators: displacement, acceleration and vibration level, the influence of different speeds and different weights of the vehicle vibration on the surrounding soil and reasonable control distance was analyzed. This paper provides reference and guidance to avoid the influence of traffic dynamic load when designing and constructing.

#### 1. Introduction

Highway dynamic load refers to the force exerted on the road by vehicles during driving. Its magnitude changes with the change of surrounding environment. It is instantaneous change, cyclic and unequal size[1], so the power is much smaller than the vibration of the earthquakes, volcanoes and tsunamis. However, it could affect the surrounding building, the durability of structures[2], the living comfort and health[3] and some work[4], etc. The inevitable trend of faster vehicle speeds, more traffic flows and the increasingly close connection between road and construction leads to the increasing impact of traffic load on new or existing buildings, which needs to be paid more attention[5].

In response to the influence of vibration on the surrounding environment, the International Organization for Standardization (ISO) as well as Germany, Britain and the United States governments put forward regulations on vibration restriction[6][7]. In China, the vibration standard of urban area is mentioned in 'Urban Regional Environmental Vibration and Measurement Methods'[8] published in 1988 without detailed provisions to provide regulation for design and construction. At present, the common practice is to equivalent dynamic load to static load which is not scientific enough obviously.

In order to cope with the gaps, scholars made research and analysis. Dodds et al. defined road roughness as the determining function of vehicle deviation from the flat road [9]. Barker simplified the plane load on the pavement to the static load[10]. Xu et al. used the finite element simulation to study the impact of load of vehicles at the pit side on the foundation[11]. Tang et al. established a mechanical behavior model to investigate the influence of factors on dynamic stress[12]. Lu et al. analyzed the influence of pavement level on dynamic stress by numerical simulation[13]. Xiong et al. used indoor model tests to study the changes of soil properties under traffic cyclic loading[14]. Liu et al. studied the crack resistance of concrete under traffic load[15]. Significant achievements and breakthroughs have

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been made by researches, but the results are still a certain distance from guiding engineering practice.

In order to study the transmission characteristics of traffic dynamic load caused by vibration and the engineering safety in vibration for further checking, the propagation characteristics of vibration waves formed by vehicles in the surrounding roads of foundation pit enclosure are investigated in this paper by combining field monitoring and numerical simulation. Furthermore, the influence of the vibration on the surrounding environment is analyzed in combination with the indirectly related specifications.

### 2. Field vibration monitoring

#### 2.1 Vibration monitoring setting

To obtain the original data of vibration caused by vehicles passing near the construction site, acceleration sensors were arranged on 5 measurement points (abbreviating as MP in the following context) between the road and the envelope to carry out vibration monitoring. In order to observe the vibration of soil (rather than asphalt), holes were made until the undisturbed soil. According to the site conditions, set the horizontal direction parallel to the road surface as X direction with the vehicle travel direction as north is positive, the direction perpendicular to the road surface as Y with the direction far from the road surface as east is positive, the vertical direction as Z direction with the top as positive (Figure 1).

The equipment used to pick up vibration signals in real time is the MB-30 three-directional force balanced acceleration sensor whose range is  $\pm 1$ g and measured acceleration resolution is 0.0001g and the sampling frequency identification range is 1-100Hz.



(a): layout of measuring points, (b): Sensor coordinate diagram, (c): photo of sensor

#### 2.2 Vibration monitoring results and analysis

2.2.1 Initial condition test. When there are no vehicles, the 10-second monitoring data of the 5 MPs can be seen in Figure 2. In the absence of traffic load, the vibration acceleration will not attenuate to 0, due to the influence of natural vibration of soil and other factors on the construction site. However, the vibration amplitude caused by the above influence is maintaining between  $\pm 0.005$ m/s<sup>2</sup>. Therefore, it can be considered that the vibration influence within this range can be ignored.





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Figure 2. Time-history curve of soil acceleration when no vehicles passing by(10s) (a): Curve of X direction, (b): Curve of Y direction, (c): Curve of Z direction

2.2.2 Traffic load monitoring for specific vehicles. In order to quantitatively investigate the influence of a single vehicle on soil vibration, the soil vibration of a single car, bus, no-load concrete tank and full-load concrete tank passing through the MPs at different speeds were recorded. Cars as well as buses and concrete tanks passing at low speed (20km/h) will not significantly affect the time-history curve of acceleration measured at MPs. Buses passing at a moderate speed (40km/h) have little influence at the MPs. The above vibration data and curves will not be reflected in the following text.

The influence of no-load (21.5t) and full-load (68.1t) concrete tanks passing above the medium speed on each MP is relatively obvious. Since the vibration in the Z direction plays a major role, the timehistory curves of acceleration in the Z direction of each measurement point are drawn. The time-history curve of the acceleration of soil mass vibration caused by the medium speed (35km/h) and high speed (48km/h) of the full load concrete tank (68.1t) passing through the MP is shown in Figure 3. The timehistory curve of the acceleration of the soil induced by the medium speed (40km/h) and high speed (60km/h) of the no-load concrete tank( 21.5t) passing through the MP is shown in Figure 4.

In Figure 3, when the speed of full load concrete tank is 35km/h, the maximum vibration acceleration can reach  $\pm 0.038$ m/s<sup>2</sup>. When the speed is 45km/h, the maximum vibration acceleration can reach  $\pm 0.055$ m/s<sup>2</sup>. The MP1 and MP2 were affected significantly while MP3 and MP4 fluctuated slightly, and the curve of the MP5 was relatively stable. In Figure 4, when the speed of no-load concrete tank is 40km/h, the maximum vibration acceleration can reach  $\pm 0.038$ m/s<sup>2</sup>, and when its speed is 65km/h, the maximum vibration acceleration can reach  $\pm 0.038$ m/s<sup>2</sup>, and when its speed is 65km/h, the maximum vibration acceleration can reach  $\pm 0.045$ m/s<sup>2</sup>. The MP1 and MP2 were affected significantly while the MP3 fluctuated slightly, and the curves of the MP4 and MP5 were relatively stable.

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Figure 3. The acceleration curve of the soil vibration when full concrete tank passing through (a): at medium speed, (b): at high speed



Figure 4. The acceleration curve of the soil vibration when empty concrete tank passing through (a): at medium speed, (b): at high speed

## 2.3 Chapter Summary

In this chapter, the vibration caused by traffic load on the engineering site is monitored and the data is analyzed to form the following conclusions.

1. The increasing of the vehicle speed and weight will increase the vibration and influence distance.

2. Without traffic dynamic loads, the vibration in soil will not disperse to zero.

3. The vibration caused by heavy vehicles (such as concrete tank) is larger and could not be ignored when the distance from the road is less than 12m.

# 3. Numerical simulation of soil vibration induced by vehicle movement

## 3.1 Introduction of the numerical simulation work

According to the field monitoring results of soil vibration in the previous chapter, the concrete tank has a greater impact on soil vibration and the direct impact range of vibration is about 12m. In order to further study the soil vibration caused by traffic dynamic load, the general finite element software ABAQUS and its subroutine DLOAD were used to simulate the dynamic process of concrete tanks which provide greater impacts on soil vibration to analyze the characteristics of soil vibration (Table 1).

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Table 1. Model setting parameters						
Model Number	Introduction	Weight	Speed			
Model 1	Full load/Medium speed	604	40km/h			
Model 2	Full load/High speed	081	65km/h			
Model 3	No load/Medium speed	21+	40km/h			
Model 4	No load/High speed	211	65km/h			

## 3.2 Introduction to the Model

*3.2.1 Geometric model.* According to the actual engineering conditions, intercept 31m roads and surrounding soil around the construction site (Figure 5). The pavement and soil layer are divided into 66,240 C3D8R (continuous stress, 3d, 8-node, reduced order integral element) elements.



Figure 5. Numerical simulation geometric model and element division (a): Geometric Model; (b): Elements

*3.2.2 Material model.* According to the survey results, the soil is divided into six layers(Table 2). Table 2. Material model parameters

	Thickness (m)	Density $(kg/m^3)$	Youngs modulas	Poisson's ratio	Damping ratio
Pavement	1	2500	1.4e9	0.25	0.03
Sand	2	1750	5.7e6	0.2	0.05
Clay	4	1940	5e6	0.25	0.05
Clay	4	2000	1.5e7	0.2	0.05
S-Clay	6	2060	1.23e7	0.25	0.05
Clay	11	2050	4.5e7	0.15	0.05
Clay	18	1930	4.5e7	0.2	0.05

*3.2.3 Load and boundary conditions.* Fixed constraints were applied to the lower side of the model, and symmetric constraints were applied to the left and right. Initial ground stress and gravity were set for the entire model. Uniformly distributed loads with magnitude of 11666.7pa and 37777.3Pa were applied to simulate weights of no-load(21t) and full-load(68t) concrete tanks, respectively.

*3.2.4 DLOAD subroutine introduction*. Since the ABAQUS finite element software cannot directly apply the moving load to the finite element model, the user needs to develop the subroutine DLOAD. Schematic diagram of vehicle dynamic load and measuring point setting (Figure 6).



Figure 6. Schematic diagram of vehicle passing and measuring points setting (unit: m)

*3.2.5 Time step setting.* Prestress and gravity of soil and pavement should be applied firstly. Dynamic load of vehicles should be applied afterward. Time step settings is in Table 3.

Step name	Step type	Job	Time (s)	Total time(s)
Initial	Initial	N/A	N/A	N/A
Geo	Geostatic	Geostress and gravity	0	0
Pressure	Dynamic Explicit	Vehicle load	3	3

# 3.3 Simulation results and analysis

*3.3.1 Vibration comparison and analysis in z direction of each measuring point.* In this section, the extraction and analysis of the vibration data in the Z direction of each MP would be focused on. Considering that the vibration produced by the full load concrete tank is more significant, the vibration curves of each MP in Z direction when the full load concrete tank (vehicle weight 68t) is running at medium speed (40km/h) and high speed (65km/h) are shown in Figure 7 and Figure 8.



Figure 7. Curves of z direction when the full concrete tank truck passing through at medium speed (a): acceleration-time curve, (b): displacement-time curve



Figure 8. Curves of z direction when the full concrete tank truck passing through at high speed (a): acceleration-time curve, (b): displacement-time curve

From Figure 7 and Figure 8, it can be seen that the vibration amplitude caused by the full-load concrete tank running at high speed is larger, but the influence on vibration frequency is not obvious. The increasing of the distance from the road could lead to a decrease of the amplitude and the frequency. In MP1-MP4, within the scope of the dynamic load to the influence of the vibration is strong. In MP5, the traffic load effect on vibration is weak. In MP6, traffic load caused by soil vibration is negligible.

3.3.2 Comparison and analysis of vibration influence of each MP. In order to quantitatively study the influence intensity of traffic load vibration and give advice on the control distance, this section will make an analysis with reference to the provisions on vibration influence. According to the international standard ISO2631, the vibration level is recorded as VL and the unit is dB.

$$VL = 20\log_{10}\frac{a'}{a_0} \tag{1}$$

Where the modified acceleration value can be calculated by the following formula:

$$a' = \sqrt{\sum a^2 \cdot 10^{0.1c_f}} \tag{2}$$

Where a represents the effective value of vibration acceleration, and  $a_0$  is the reference acceleration whose specified value is  $10^{-6}$ m/s<sup>2</sup>.  $C_f$  is the sensory modification value of vibration acceleration whose value is shown in Table 4. International standard ISO2631 sets the limit value of vibration in different types of buildings based on the comfort level of human body (

Table 5).

 Table 4. Vibration acceleration sensation correction in ISO2031/1-1985

X7 / 1 1 /	Modification value/dB	-6	-3	0	0	0	-6	-12	-18
vertical direction	Allowable deviation/dB	±2	±2	±1.5	=1	0	$\pm 1$	$\pm 1$	$\pm 1$
Havizantal direction	Modification value /dB	3	3	-3	.7	-9	-15	-21	-27
norizontal direction	Allowable deviation /dB	±2	±2	±1.5	=1	$\pm 1$	$\pm 1$	$\pm 1$	$\pm 1$

		Vibration level/dB			
Zone	Time	Continued vibration		Transient	vibration
		H-axis	V-axis	H-axis	V-axis
Sensitive aera	All day long	71	74	71	74
Residence	Nighttime	74	77	74-97	77-110
Office	All day long	83	86	113	116
Workshop	All day long	89	92	113	116

Table 5. Vibration limits in buildings in ISO2031/1-1985

The vibration levels in Z direction at each MP were calculated, and the curve are shown in Figure 9. As it is located at the construction site, the vibration limit could refer to the workshop in

Table 5. When the full-load concrete tank is running at medium speed, the MP4 and beyond can meet the requirements. When full load concrete tank is running at high speed, the MP5 and beyond can meet the requirements.

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Figure 9. The vibration level curve of z direction when the full concrete tank truck passing through (a): at medium speed, (b): at high speed

### 3.4 Chapter summary

In this chapter, the vibration characteristics of soil under traffic load are numerically simulated and the following conclusions are obtained.

1) Vibration waves in vertical direction of soil vibration play the most important role.

2) The faster the vehicle travels, the larger the vibration amplitude will be, but the influence on the vibration frequency is not obvious. The farther the distance is from the road, the smaller the vibration amplitude will be and the smaller the frequency will be. This indicates that the amplitude and frequency will attenuate during the propagation of vibration.

3) On the construction site, the direct impact of soil vibration caused by conventional non-freight vehicles will be difficult to detect after about 7m, while the direct impact of soil vibration caused by conventional freight vehicles will be difficult to detect after about 12m. The increase of vehicle load and the acceleration of vehicle speed can enhance the impact range of vibration.

4) If only the most adverse factors in traffic (high-speed but not overspeed driving full load concrete tank truck) are considered, the distance of more than 12m from the roadside can meet the requirements of human comfort.

#### 4. Conclusions

In this paper, the propagation characteristics of vibration waves in soil under the influence of traffic dynamic load are studied through field monitoring and numerical simulation of traffic dynamic loadinduced vibration in the area between the construction site envelope and pavement. In the absence of a direct guide specification, the influence range of vibration wave is studied by referring to the indirectly related specification through three indicators of displacement, acceleration and vibration level, and the following conclusions are drawn.

1. Vibration wave caused by traffic load is shear wave.

2. During the propagation of vibration, the amplitude and frequency will attenuate

3. The influence of speed on amplitude is great, but the influence on frequency is not obvious. Both speed and vehicle weight can influence the vibration and influence range.

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