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Analysis of Vibration Response Induced by Trains on High Embankment of Ba-zhun Heavy-Load Railway

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ABSTRACT: According to the typical section of high embankment subgrade of Ba-zhun heavy-load railway, a finite element model of dynamic response of high embankment under load of heavy-load train was adopted. Based on the improved vertical dynamic coupling system of vehicle-track, the time history response of sleeper force under different heavy-load train velocities was calculated, which was then set as the external excitation of the finite element model. After the model calculation, the dynamic response of high embankment subgrade induced by the train load of heave-load railway and its distribution law along the depth of high embankment were analyzed and discussed.

KEYWORDS: Heavy-load railway, Train load, Vibration response, High embankment, Finite element

INTRODUCTION

The heavy-load railway has attracted the attention of different countries for its advantages of high transportation capacity and high transport efficiency. According to the heavy-load criterion made by the IHHA in 2005, the heavy-load railway must meet up at least two of the three standards (Qian, 2007): a. the train weight should at least reached 8000 tons; b. the axle weight reached above 27 tons; c. the annual freight weight on the railway line not less than 150Km attained 4000 million tons. Comparing with the normal railway, the heavey-load railway has several characteristics like more freight volume and higher traction force and traffic density, and the railway subgrade will be suffered to more powerful dynamic load and higher vibration frenquency, thus, causing the emergency capacity of strength, stiffness and stability of railway subgrade structure decreases (Li et al., 2016).

The high embankment subgrade as the most common structure in railway lines are often composed of granular fillers, and it undertakes the weight of track structure and dynamic load of trains. The properties of dispersibility and compressibility of the subgrade materials made the inevitable relative displacement between soil particles under long term dynamic cyclic loading, thus, weakening the subgrade workability. However, the design criterion of traditional railway is not suitable for heavy-load railway as the train axle load increased more and more. So, the stability of the newly built heavy-load railways need to further study (Tian, 2014; Liu, 2014; Guo et al., 2014).

In this study, a finite element model of high embankment considering dynamic response induced by heavy-load train was created, and the time history response of sleeper force under different heavy-load train velocities caculated by dynamic coupling system of vehicle-track was set as external excitation of the model, After the model caculation, the dynamic response of high embankment subgrade and its distribution law along the depth of high embankment were analyzed and discussed.

ENGINEERING GEOLOGY

The Ba-zhun heavy-load railway constructed by Shenhua Corporation is located at Erdos in Inner Mongolia, the tractive tonnage of this railway reaches at 10000 tons and its designed annual freight volume is 200 million tons. This railway has a line with 128.102km, and the subgrade was constructed in the form of high embankment between DK97+305.00~DK97+503 of this line. This paper taken the typical section of high embankment situated at DK97+454 as the reaserch objective. The height of embankment is 20.7m and its width of top surface of embankment is 12m. The thickness of top layer and bottom layer of subgrade bed respectively are 0.6m and 1.9m, the thickness of embankment below the subgrade bed is 18.2m. The embankement subgrade was divided into two parts, the slope ratio at upper embankment is 1:1.5 and the lower is 1:1.75, a width of 2m plat was set at the junction. The material used for top layer of subgrade bed is grade A filler, the bottom layer was constructed by 8% lime improved soil, and the rest embankment material is grade C filler. The Engineering-geological characteristics from top down respectively are weakly, strongly and fully weathered rock stratum. The cross section of high embankment of DK97+454 was drawn in Fig. 1.

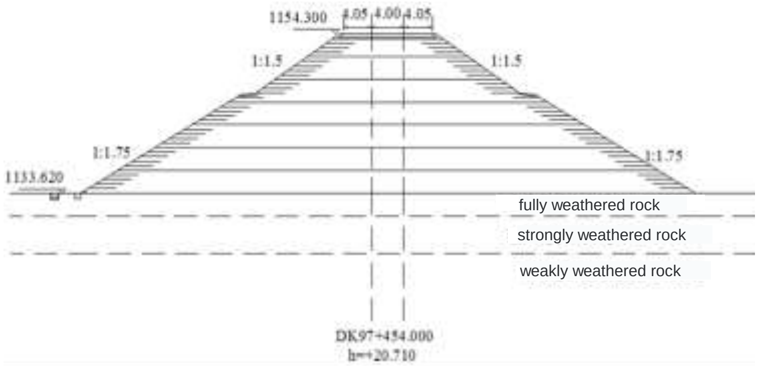

Figure 1. Cross section of high embankment of DK97+454.

NUMERICAL FEM MODEL

Model assumptions and element type

Three assumptions were taken into consideration befor the model creating: i) as the subgrade is a linear banded structure, the elastoplasticity analysis of numerical model can be considered as a plain strain problem; ii) the two-node linear plain beam element was selected to simulate sleepers, the ballast bed, embankment and foundation were simulated by the four-node double linear plain strain element; and iii) the connection between sleepers and ballast bed was secleted by using constrain element.

The choosing of model size should consider the effect of boundary effect and computation time. Considering that the model size can be efficiently scaled down by using the infinite element to simulate the boundary conditions, the four node infinite element was selected in this paper. The thickness of foundation in this model is as twice as the height of high embankment, and its width is as one point five times as the base width of foundation. Fig.2 was the numerical model of high embankment subgrade.

Constitutive model and parameters of materials

The sleeper and ballast layer of high embankment are mainly kept in the elastic state under the dynamic loading induced by trains, so, the linear elastic constitutive model was selected for the sleeper and ballast layer in the computing model. The Drucker-Prager model was adopted to simulate the materials of foundation and subgrade because of the plastic characteristics of fillers. The parameters of materials based on the Drucker-Prager model can be deduced from the constitutive model parameters of Mohr-Coulomb. The sleeper parameters were shown in Tab.1, and parameters of embankment model were shown in Table 2.

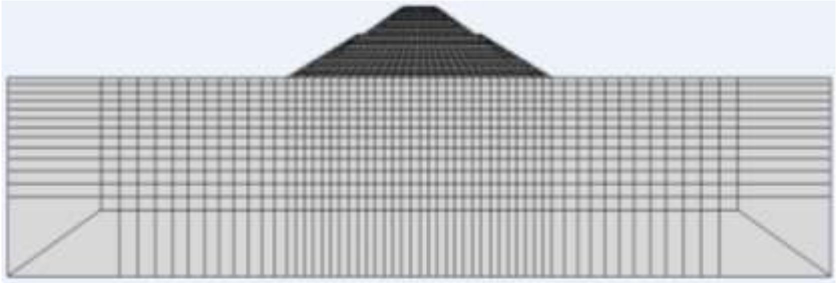

Figure 2. Finite element modeling of high embankment subgrade.

Table 1. Parameters of sleepers.

Part of steel rail	Elastic modulus （kPa）	Poisson ratio	Gravity N.m-3	Inertia moment m.kg.s2
Both ends	3×107	0.04585	-26	0.000159
Middle	3×107	0.0339	-26	7.639×10-5

Train loading

Based on the unified theory, the train-track-subgrade dynamic coupling system was developed by Zhai Wanming team (Zhai, 2007), and the research team of Ling Xianzhang in HIT improved this system and named it as ZL-TNTLM (Li, 2015), see Fig. 3. By using this improved dynamic coupling system, the time-history curve of sleeper force under different train velocity can be calculated, which can be set as the external excitation of embankment model and then help to study the vibration response of high embankment induced by the heavy-load train. In this paper, the DF4 locomotive and C75 freight train were preferred as the study objective, and the train formation in the model is DF4-C75-C75-C75. The parameters of vehicle model see Tab.3.

Table 2. Parameters of modeling materials.

Materials	Elastic modulus （kPa）	Poisson ratio	Density （g/cm3）	Cohesion （kPa）	Friction angle （°）	Damping ratio
Weakly weathered rock stratum	600000	0.24	2.53	100	43	0.05
Strongly	80000	0.27	2.1	42	40	0.05

weathered rock stratum						
Fully weathered rock stratum	40000	0.3	2.05	20	38	0.05
Embankment layer below subgrade bed	37000	0.3	1.95	12	34	0.05
Bottom layer of subgrade bed	64000	0.3	2.00	52	37	0.05
Top layer of subgrade bed	110000	0.28	2.14	34	40	0.05
Ballast bed	200000	0.25	2.2			0.03

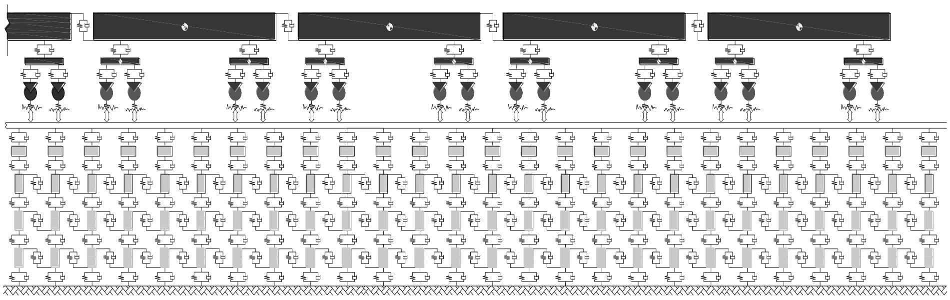

Figure 3. Modified coupling dynamic model of train-track system.

NUMERICAL RESULTS AND ANALYSIS

Dynamic time history

The dynamic time history curves of the ballast bed surface induced by heavy-load train were shown in Fig. 4. From the figure, we see that when each train bogie passes the measuring point, the dynamic stress on the ballast bed surface can reach to a peak value and each of the dynamic time history curves was an unimodal curve. Meanwhile, the dynamic stress induced by locomotive is greater than that induced by freight train. Considering that the axle load of locomotive is heavier than that of freight train, we can infer that, the axle load has a significant effect on the dynamic stress of embankment, the heavier the axle load, the greater the dynamic stress.

Table 3. Parameters for heavy load train.

Parameters	DF4 Rolling stock	C75 Freight train
Vehicle weight (kg)	72456	91800
Bogie weight (kg)	15293	1510
Wheel set mass (kg)	5827	1295
Train nutation inertia (kg·m2)	1170000	4220000
Bogie nutation inertia (kg·m2)	5910	1560
Primary suspension stiffness (N/m)	1920000	0
Secondary suspension stiffness (N/m)	5360000	10280000
Primary suspension damping (N·s/m)	200000	0
Secondary suspension damping (N·s/m)	200000	100000
Half length of bodywork (m)	5.642	4.35
Bogie wheel base (m)	1.25	0.875

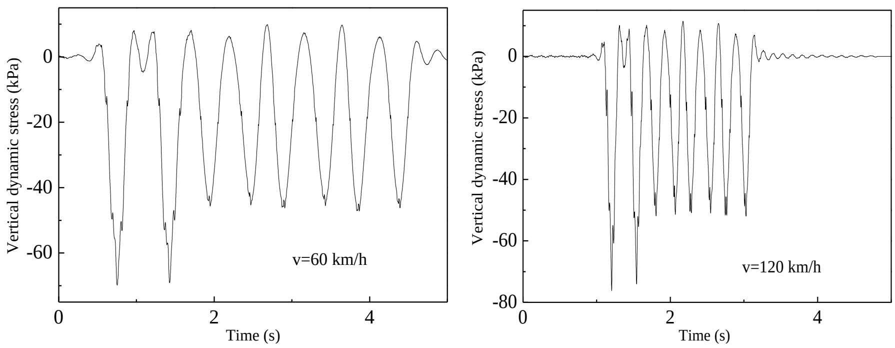

Figure 4. Time history curves of dynamic compressive stress at ballast bed surface.

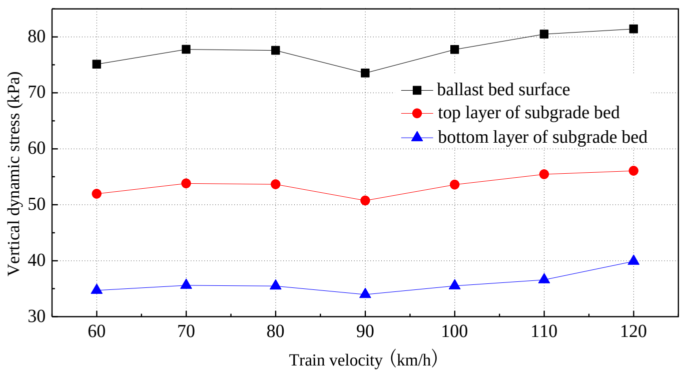

Figure 5. Effect of train velocity on the maximum dynamic compressive stress.

Fig. 5 shows the effect of train velocity on the maximum dynamic compressive stress. From the figure, the maximum dynamic stress of ballast bed and subgrade bed is not increasing with the increase of train velocity, but presents a tendency of fluctuation. We also found that the dynamic stress at different soil layers and different depth are not the same.

From Fig. 6, the vertical dynamic stress in the embankment induced by heavy-load train presents a non-linear relationship with the depth of embankment, and the vertical dynamic stress are decreasing with the depth of embankment increases. The reduction of the dynamic stress in the ballast bed and top layer of subgrade bed is sharp, but, the decreasing tendency changed into gently as the depth of embankent increase. The attenuation of vertical dynamic stress in the ballast bed is about 30%, after spreading through the top layer of subgrade bed, the stress attenuating is about 50%, the value can be achieved at 75% when spreading through the bottom layer of subgrade bed, and the total stress attenuating is more than 80% at the depth of 5m from the ballast bed surface.

Acceleration time history

The subgrade vibration acceleration is an important parameter used for judging the effect of vibration on the subgrade failure. Fig.7 shows the acceleration time history curves of ballast bed surface at different train velocity. From the figure, each acceleration time history curve has an obvious periodic oscillating characteristic and an evident vibration peak.

Fig. 8 shows the effect of train velocity on acceleration amplitude. From the figure, we can obviously know that the acceleration amplitude is enlarged as the train velocity increased. As the speed of train increased from 60 km/h to 120 km/h, the vertical acceleration amplitude at the ballast bed surface increased by 125.7% and it at the surface of subgrade bed increased by 85.5%.

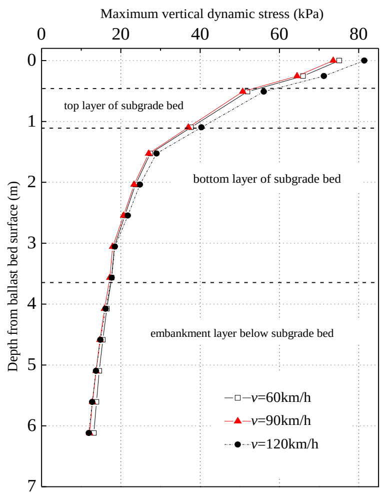

Figure 6. Distribution curves of maximum vertical dynamic stress alone the depth.

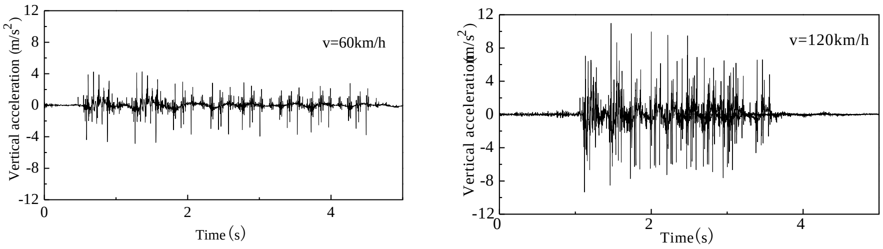

Figure 7. Acceleration time history curves of ballast bed surface.

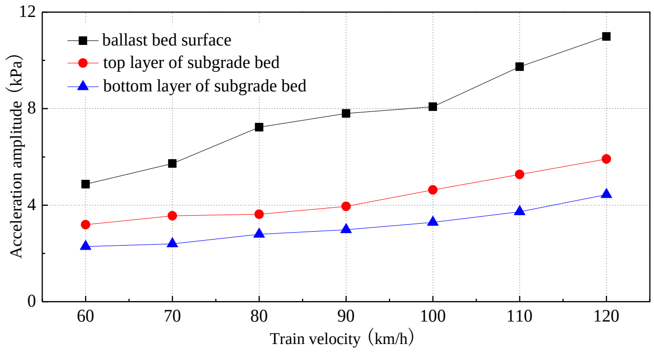

Figure 8. Effect of train velocity on acceleration amplitude.

Distribution curves of vertical acceleration amplitude along the depth were drawn in Fig. 9. The distribution law is similar to that of dynamic stress amplitude along the depth, the curves present a non-linear characteristic, and the verticle acceleration amplitude decreasing as the depth increasing. But, the attenuation velocity of acceleration amplitude along the depth of subgrade is greater than that of dynamic stress amplitude. As the speed of train reached at 90km/h, the vertical acceleration amplitude in the ballast bed decreased by 49%, after spreading through the top layer of subgrade bed, the acceleration amplitude attenuating is about 61.8%, the value can be achieved at 85.7% when spreading through the bottom layer of subgrade bed, and the total stress attenuating is more than 91.1% at the depth of 5m from the ballast bed surface.

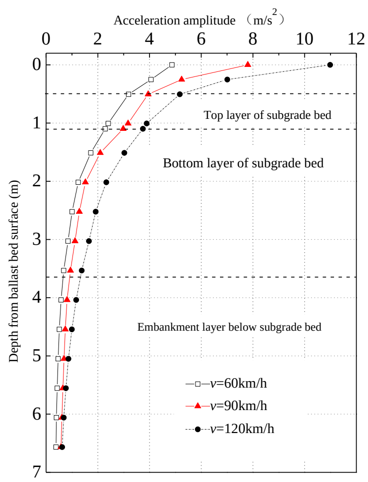

Figure 9. Distribution curves of vertical acceleration amplitude along the depth.

CONCLUSIONS

According to the typical section of high embankment of Ba-zhun heavy-load railway, this paper provides a numerical model of embankment considering the vibration loading of heavy-load train, and the external excitation of the finite element model was calculated by the ZL-TNTLM system. The dynamic response of high embankment induced by the heavy-load train was thoroughly discussed, and the mainly results are list as follows.

Under the loading of heavy-load train, the dynamic stress on the ballast bed surface can reach to a peak value and each of the dynamic time history curves was an unimodal curve; each of the acceleration time history curves has an obvious periodic oscillating characteristic and an evident vibration peak.

The vertical dynamic stress and acceleration amplitude are increasing as the axle load of heavy-load train increased.

The maximum dynamic stress in the embankment is not increasing with the increase of train velocity, but presents a tendency of fluctuation. But, the acceleration amplitude improved obviously with the increase of train velocity.

The distribution law of dynamic stress in the embankment along with the depth of subgrade is similar to that of vertical acceleration amplitude. Both of them present a non-linear relationship with the embankment depth and decreasing as the depth increases.

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