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ANALYSIS OF THE STRESS CHARACTERISTICS OF CFG PILE COMPOSITE FOUNDATION UNDER IRREGULARITY CONDITION

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ABSTRACT

By the excitation load function corresponding to the irregularity management standard the vertical load of the train is simulated. Based on the finite difference software FLAC3D the three-dimensional dynamic coupling finite difference model of track-embankment-pile-soil composite foundation is established. Focuses on the analysis of the dynamic response characteristics of the embankment, pile and soil foundation caused by the change of foundation, pile and cushion elastic modulus and cushion thickness. Results show: by the excitation load, the centre pile dynamic stresses are maximum, piles dynamic stress away from the centre side pile decreases gradually. The dynamic response of the pile and soil caused by subgrade surface elastic modulus variation has a little effect with more obvious by the cushion effect. With the increase of elastic modulus and thickness of cushion, the dynamic interaction between pile and cushion is increased while the dynamic interaction between soil and cushion is weakened. Therefore, the bearing capacity of the pile is fully utilized. With the increase of the elastic modulus of the pile, the dynamic stress of pile top increases correspondingly, but the dynamic stress increases gradually, and the pile bears most of the load, thus effectively reduce the dynamic load of the foundation soil.

KEYWORDS

High-speed railway, Geometric irregularity, CFG pile composite foundation, FLAC-3D, Dynamic analysis.

INTRODUCTION

Soft ground is one of the most important problems in the construction of high-speed railway [1]. In order to reduce the settlement of subgrade and improve the stability of train operation, it is necessary to reinforce the soft soil foundation [2, 3]. As a method of reinforcing soft soil foundation, CFG pile is widely applied in high-speed railway soft soil foundation reinforcement [4, 5, 6]. But the high-speed railway soft foundation settlement characteristics is not only influenced by the strengthening type of foundation [7, 8], it is also affected by [9, 10] the pile length, pile diameter, pile spacing and other factors [11, 12], as well as the influence of train dynamic load performance [13, 14, 15]. Therefore, this paper will analyse the dynamic stress distribution characteristics and the change law of the composite foundation in the process of train operation.

As a kind of external excitation, track irregularity is the main cause of vibration of vehicle system [16]. Therefore, the description of the random variation of track irregularity is an important basis for analysing the dynamic characteristics of vehicle track system. Based on this idea, a load function which can be composed of static load and a series of sinusoidal functions can be used to simulate the vertical load[8].During the train operation, the design parameters of the various parts of the pile-soil composite foundation system, such as bedding, cushion, pile body different degrees affects the dynamic characteristics of the whole system. Therefore, it is necessary to analyse the factors that affect the dynamic characteristics of the system. This paper will use the finite difference software FLAC3D to analyse the CFG pile composite foundation soil dynamic response under the train vibration load.

ANALYSIS MODEL

Train Load Model.

The trainload is very complex, which is affected by many elements of the rail system. The following factors should be considered in the simulation of trainloads:

① The power performance of the locomotive
② The Influence of speed
③ The influence of the track irregularity
④ The rail top surface uneven wear effect caused by the eccentric wheel
⑤ The continuous irregularity in wheel tread wear caused by uneven irregularity alone.

A lot of theoretical research and experimental work of the British Railway Technology Centre for many years show that the main causes of the vertical wheel rail force is composed of various irregularities and local wheel flat scar [17].

The experiments also show that the vertical wheel rail force occurred mainly in the three-frequency range:
① Low frequency range (0.5~10 Hz). It almost entirely produced by the relative motion of the vehicle body to the suspension parts
② Intermediate frequency range (30~60 Hz). It is because of the rebound effect of wheel set quality under spring on rail
③ High frequency range (100~400 Hz). It is generated by the wheel rail contact surface resistance with rail movement. The results show that the wheel rail force is more severe in the intermediate frequency and low frequency range, and the high frequency range mainly affects the dynamic response of the vehicle body.

It can be seen from the above experimental results, when considering the use of seamless line, the main reason influence on wheel rail force is track irregularity and rail surface waveform wear effect. In addition, the foundation of high-speed rail track is more solid. So the irregularity condition mainly belongs to random irregularity.

Some domestic scholars have made some achievements in the simulation of trainload. Liang Bo and Cai Ying [18], based on the track geometric irregularity, by exciting force function corresponding to irregularity management standards to simulate the vertical dynamic load of the train, the dynamic finite element analysis is carried out and the results are in good agreement with the measured values, which proves the correctness of the model to a certain extent. Liang Bo and Luo Hong[18] in consideration of the basic mechanism of vibration load, taking into account the overlap between wheel and rail forces and dispersion of sleeper, the exciting force function to simulate the train load is optimized. The optimized excitation load function is a comprehensive expression formula. It not only considers the mutual superposition of wheel rail forces between the adjacent wheel sets and the dispersion of sleepers, but also considered the vibration caused by track irregularities and other factors. It provides reference for the determination of dynamic load and dynamic response analysis of high-speed train. Feng Junhe and Yan Weiming [20] studied the numerical simulation method for two kinds of random excitation loads at present more commonly used in engineering. By introducing the frequency response function and track irregularity spectrum, he optimized the trainload numerical algorithm and the calculation model, and in the numerical calculation used Fourier fast numerical algorithm to improve the efficiency and reliability of the trainload simulation. Finally, the rationality and efficiency of the two new methods are demonstrated by simulation.

In order to solve the problem of the lack of precision in the method of track irregularity and the difficulty of calculation of vehicle-track coupling model, Wang Jie and Song Ruigang,et. [21] established the simplified model of train load. In Simulink, the change curve of subway train load is simulated, and the frequency component of train load is analysed by fast Fourier transform, the simulation expression formula of subway train load is obtained. The model established by means of this analytical method is simple and has fast calculating speed. At the same time, it also has higher reliability than the irregularity method, which can meet the needs of general research. Huang Bo [22], by use of GDS three triaxial instrument, completed the high vibration cycle three axial tests of typical cohesive soil along high speed railway, studied under different experimental conditions the specimen deformation, pore pressure variation development law and the critical cyclic stress ratio variation. Research suggests that the half sine wave can be used to simulate the high-speed train load under the condition of drainage to obtain the maximum possible soil deformation and critical dynamic stress ratio, which simplifies the test process and shortens the test time greatly. Jiang Hongguang [23] built a sequential dynamic loading system, which is composed of 8 dynamic hydraulic exciter control systems, 1 set and 1 set of counter force frame and realized the effective simulation of the train load of the highest speed 360km /h in laboratory. At the same time, he built a model of the 1: 1 scale type I slab track subgrade in the laboratory, through the control of filler gradation, target density and moisture content ensure compaction coefficient, subgrade foundation coefficient and deformation modulus to meet the requirements of the design specifications. On the basis of the test equipment and test model, the dynamic response and long term performance of track subgrade under moving load of wheel axle are reproduced. Other scholars [15, 16] have also studied the relevant content.

This article refers to the British geometric irregular management standards, see Table 1.

Tab. 1 - British geometric irregular management standards

control conditions	wavelength /m	railway versine /mm
the smoothness of the train	50	16
	20	9
	10	5
the additional dynamic load acting on the line	5	2.5
	2	0.6
	1	0.3
waveform wear	0.5	0.1
	0.05	0.005

The improved excitation force function proposed in literature [18] is used to simulate the train load.

$$F(t) = k_1 k_2 [p_0 + p_1 \sin(\omega_1 t) + p_2 \sin(\omega_2 t) + p_3 \sin(\omega_3 t)] \tag{1}$$

where： $F(t)$ is train dynamic load; p_0 is wheel static load; p_1 , p_2 , p_3 are vibration load corresponding to a certain frequency; k_1 is superposition coefficient which reflects the superposition of adjacent wheel and rail; k_2 is dispersion coefficient, which reflects the dispersion effect of the load on the sleeper. The quality of train spring is M_0 . The corresponding amplitude of vibration load is:

$$P_i = M_0 a_i \omega_i^2, \ (i = 1,2,3) \tag{2}$$

Where： a_i is corresponding vector height; ω_i is the circular frequency of the corresponding train under the speed of irregularity vibration. Corresponding calculation formula is:

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$$\omega_i = \frac{2\pi v}{L_i} \quad (3)$$

Where v train speed is L_i is the corresponding typical wavelength.

CHR train axle 170kN，take the single wheel load 85 Kn, train unspring mass M_0 is 2000kg; Take k_1 1.45 with k_2 0.75；Design train speed is 300km/h Wavelength and vector height: L_1 =10m, a_1 =5mm; L_2 =2m, a_2 =0.6mm, by calculation P_1 =27.4Kn, P_2 =82.2Kn; ω_1 =52.36, ω_2 =261.8, ω_3 =1047.2.The frequency of ω_3 is higher, which mainly affects the dynamic response of vehicle body. In this case, it is reflected in the dynamic response of the train body, the exciting force function is an irregular waveform, the first 0.02 vibration curves are shown in Figure 1.

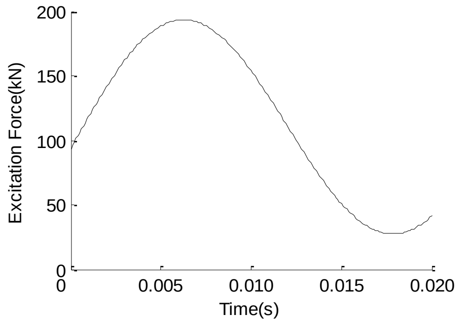

Fig.1 - Exciting force time history curve

Finite Difference Model

FLAC3D (Fast Lagrange Analysis of Continua 3 Dimensional)) is a continuous medium mechanics analysis software developed and popularized by Itasca company, which is mainly used in the field of geotechnical engineering. The fast Lagrange analysis method solves the governing differential equations of the field by means of explicit finite difference schemes. At the same time, combined with the discrete model of the hybrid element, the yield, plastic flow, softening and deformation of the material can be accurately simulated. In view of the above mentioned, the three-dimensional fast Lagrange analysis method, especially in the elastic-plastic analysis of materials, large deformation analysis has a unique advantage. Therefore, by the finite difference software FLAC3D this paper establishes the three-dimensional dynamic coupling analysis model of high-speed railway subgrade, and studies the stress response of the pile and soil under the dynamic load. The design surface layer of subgrade bed thickness is 0.7 m; thickness of bottom layer is 2.3 m; subgrade slope ratio is 1: 1.5.The CFG pile composite foundation pile net structure is adopted in the foundation. The model is a single row piles. The pile diameter is 0.5m with 15m long, 2.5m spacing and 0.6m thick gravel cushion at pile top, the horizontal width to pile shaft centre is around the 23.5m, total width is 47m, deep is 40 m, and along the line direction is 3m.

In the initial stage of the model, i.e. in the static stress calculation, the boundary condition of the model is horizontal and vertical constraint and the lateral boundary is the horizontal constraint. In the process of dynamic calculation, the boundary condition of the static calculation is removed, the free field boundary is adopted, and local damping is used in mechanical damping. Three dimensional finite difference model of pile -soil composite foundation is shown in Figure 2. The pile number of the centre pile is No. 1.Pile along the centre pile is No. 2 and No. 3.

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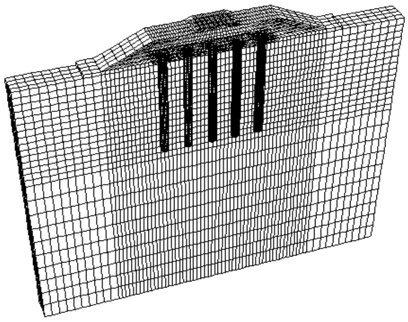

Fig.2 - Three-dimensional finite difference model of pile-soil composite foundation

Assumed conditions

Rail, rail fastening system, sleepers, bedding surface layer, bottom layer of subgrade and embankment body and foundation structure, using 8 node solid element simulation. Taking into account the relevant adjacent structure layer stiffness difference is too large, the contact surface model of the upper layer and lower layer interface of sleepers and pile-soil contact surface were established by interface model to ensure the deformation compatibility between the layers. The rail, sleeper is assumed to be isotropic linear elastic material; surface layer of subgrade (gravel), the bedding bottom layer (AB group filler -China Railway Subgrade Design Code - TBJ447-2005) [24]). Mainly based on the soil type and the content of particle diameter less than 0.075mm, and considering the compaction requirements and the use conditions, the subgrade fillers are divided into group A, B, C, D and E. Fine-grained soil content of group A is less than 15%, which is high-quality subgrade filler. Fine-grained soil content of group B is 15% to 30%, which is good subgrade filler. Therefore, rock blocks and coarse-grained soil that meet the design requirements can be used as AB group fillers) and the embankment body and foundation soil are assumed to be plastic material for Mohr-Coulomb elastic-plastic material.

Boundary conditions

For the numerical simulation of the dynamic problem, it is considered that the wave reflection on the boundary of the model will affect the analysis result. Therefore, by setting the free damper at the normal and tangential directions of the model boundary to absorb the income wave reduce the negative influence of the wave reflection of the on the analysis results. The normal viscous forces and tangential viscous forces provided by damper are calculated respectively:

$$t_n = -\rho C_p v_n \tag{4}$$

$$t_s = -\rho C_s v_s \tag{5}$$

Where v_n and v_s respectively are the normal velocity component and tangential velocity component of the model boundary; ρ is the medium density; C_p 、 C_s respectively are P-wave velocity and S-wave velocity.

Constitutive Model and Calculation Parameters

The composition of the track structure from top to bottom is the rails, rail fastening system and sleeper. The rail fastening system plays a role in damping and the limit in the track structure, and transfers the part of wheel rail force after attenuation to the sleepers, has a certain flexibility and elasticity, supports the rails and maintains the rail position. At the same time, it passes the great pressure transferred by rails to the track bed. Therefore, based on the difference of each component of track structure, the dynamic analysis model of track subgrade system is established. The constitutive model is selected by FLAC3D model, The Mohr-Coulomb model is used in the foundation soil, and the elastic model is used in other structures. Calculated parameters are shown in Table 2. In the table E is elastic modulus, μ is Poisson's ratio, ρ is density, c and φ respectively are the cohesive force and internal friction angle of soil.

Table 2 Calculation Parameters

structure layer	$E\,(MPa)$	$\rho\,(kg/m^3)$	$c\,(kPa)$	$\varphi\,(^\circ)$	μ
steel rail	210000	7800			0.20
sleeper	30000	2500			0.20
ballast	200	2200			0.20
bedding surface	100	1950			0.30
bedding surface	150	1950			0.30
bedding surface	200	1950			0.30
bedding bottom	50	1900			0.35
cushion	50	2000			0.25
cushion	100	2000			0.25
cushion	200	2000			0.25
pile body	15000	2300			0.20
pile body	20000	2300			0.20
pile body	25000	2300			0.20
soft soil layer	10	1200	8.8	20	0.35
bearing layer	20	1500	15	25	0.30

RESULT ANALYSIS

We assume that the railway line along the longitudinal direction is infinite and uniform. Therefore, the dynamic response of track subgrade structure caused by trainload is basically the same. Referring to the calculation parameters in table 2, applying a vertical direction dynamic load without applying a horizontal dynamic load along the line direction, the dynamic stress wave is propagated along the embankment down, the dynamic analysis of CFG pile composite foundation embankment under the train excitation load is mainly carried out.

Dynamic Stress and Time History Curves of Pile and Embankment

Figure 3 shows the dynamic stress time history curves of pile and embankment. The dynamic response of the top of the embankment varies greatly with the excitation load, and the dynamic stress curve is similar to the excitation load curve. The dynamic response of pile top increases continuously, and local stress decreases slightly. Obviously, the dynamic stress at the top of the embankment is greater than that at the bottom of embankment. The dynamic stress peak appears at the initial loading stage, which is about -241kPa (The negative represents dynamic stress as compressive stress. The magnitude of dynamic stress is expressed as its absolute value. The same below.). The bottom dynamic stress is very small; the maximum value is about -20kPa. It is obvious that the curves of piles 1 and 2 are different. Based on the propagation velocity of dynamic stress in the embankment, the time required for the propagation of dynamic stress along the embankment is related to the material properties of the embankment. In time, the dynamic stress propagation from top to bottom of the embankment, about 0.004s or so it reaches the top of the pile No. 1 and No. 2; In the space, the dynamic stress of pile top is reduced from No. 1 central pile to No. 2 side pile.

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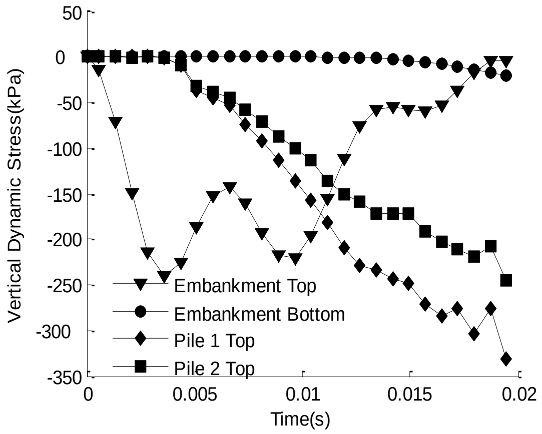

Fig. 3 - Dynamic stress time history curves of pile and embankment

Influences of Subgrade Elastic Modulus on Dynamic Response of CFG Pile Composite Foundation

Take the soil between the central pile of No. 1 and the pile top section of No. 1 and No. 2 as the analysis object. In order to analyse the influence of elastic modulus of composite foundation dynamic response, select three kinds composite of elastic modulus

(1) 100MPa surface layer+50MPa bottom layer
(2) 150MPa surface layer +50MPa bottom layer
(3) 200MPa surface layer +50MPa bottom layer

The dynamic stress change curve of the centre pile No. 1 is obtained, as can been seen in Figure 4. The dynamic stress time history curve of pile top under the excitation force is basically the same. The dynamic stress from the embankment top after a short time transfer to the top of the pile and it gradually increased. When subgrade modulus is 100MPa, dynamic stress of the pile top is the largest, it is about -344kPa. With the increase of the elastic modulus of subgrade the dynamic time history curve of pile top has no obvious change, influence of subgrade modulus of elasticity decreased gradually. The dynamic stress propagation does not exist only in the vertical direction, but it also exists in the transverse propagation. Under the interference of peaks and valleys transformation of dynamic waves, the stress wave is reflected and disturbed in the pile, the dynamic stress is agitated. We can see from Figure 5 that the dynamic stress waveform is similar to the loading waveform in a short time; with the subgrade modulus increases, the arrival time of pile-soil stress peak was ahead, that is to say the increase of the elastic modulus of embankment material improves the dynamic stress wave propagation velocity. Because of the large difference between the elastic modulus of the pile and the soil, the pile bears most of the load, the soil is only a small part of the load, maximum dynamic pile-soil stress ratio can reach 25.

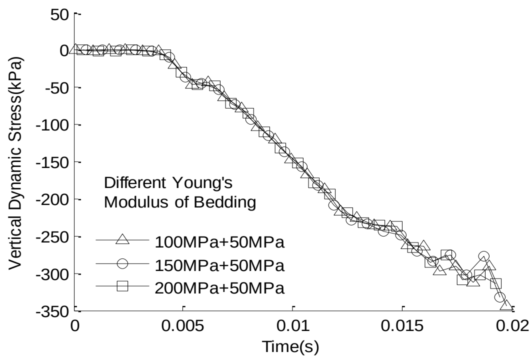

Fig. 4 - The effect on dynamic stress of pile top subgrade of elastic modulus

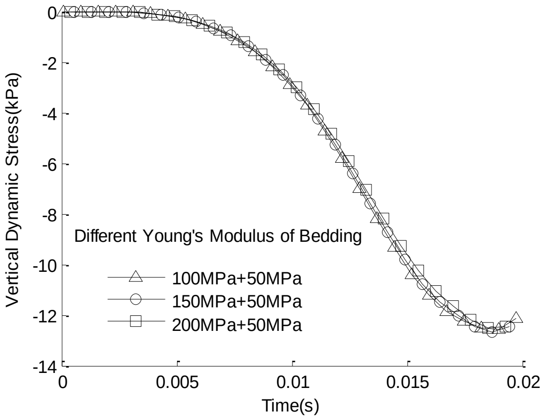

Fig. 5 - Effect on dynamic stress of soil between piles of subgrade elastic modulus

Influences of Cushion Elastic Modulus on Dynamic Response of CFG Pile Composite Foundation

We can see from Figure 6 that the dynamic stress curve of pile top caused by the change of elastic modulus of cushion is similar, and the difference is that the dynamic stress is different at different times. This shows that: the increase of the elastic modulus of the cushion intensifies the interaction between the cushion and the pile, and the dynamic stress increases with the increase of the elastic modulus of the cushion; when the elastic modulus of cushion is 200MPa, the dynamic stress of pile top is about -344kPa. In addition, under the instantaneous excitation load, with the increase of the elastic modulus of the cushion, the dynamic stress of the pile top increases obviously. In Figure 7, the change of the elastic modulus of the cushion causes the variation of the dynamic stress of soils between the piles.

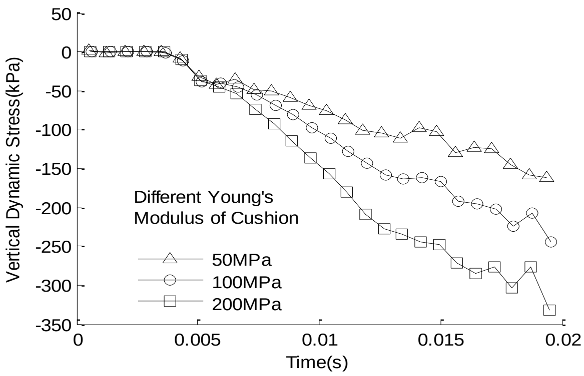

Fig. 6 - Effect of cushion elastic modulus on dynamic stress of pile top

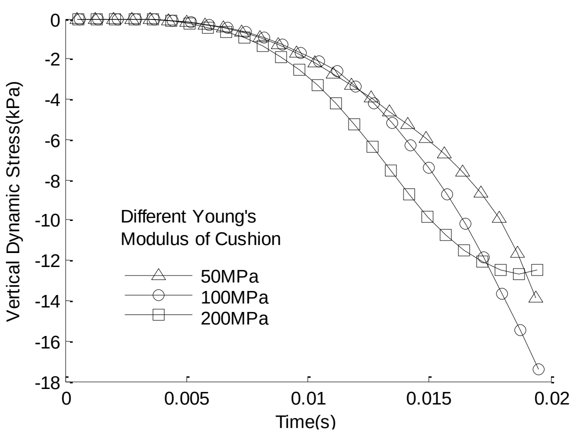

Fig. 7 - Effect of cushion elastic modulus on dynamic stress of soil between piles

In Figure 7, when the elastic modulus of cushion is 50MPa and 100MPa, the dynamic stress of soil between piles increases with the loading time; when the elastic modulus of the cushion reaches to 200MPa, the dynamic stress curve of the soil begins to change; when the elastic modulus of the cushion is 200MPa, the dynamic stress of soils between piles appears peak value; at this time, the peak dynamic stress is the smallest. To some extent, it is indicated that the bigger the elastic modulus of the cushion, the stronger the interaction between the cushion and the pile. On the contrary, the dynamic interaction between the cushion and the soil is smaller.

Influences of Cushion Thickness on the Dynamic Response of CFG Pile Composite Foundation

Design cushion thickness is 0m, 0.5m and1m. As can be seen from Figure 8 the dynamic stress curve of pile top caused by the change of cushion thickness is similar; The difference is that the dynamic stress is different at different time; the increase of cushion thickness also increases the interaction between cushion and pile, and the greater the thickness of cushion, the greater the dynamic stress of pile top. Before and after the arrangement of cushion, the dynamic stress of pile top increases significantly, the increase amplitude is larger. However, with the increase of the thickness of the cushion, the influence of the cushion thickness is gradually weakened, and the growth rate decreases. The above analysis shows that it is necessary to set cushion in the treatment of CFG pile composite foundation, the setting of the cushion makes the transfer of the upper load to the pile, and gives full play to the bearing capacity of the CFG pile, realize the economic effect.

Figure 9 shows that when the cushion is not set, with the increase of the loading time, pile-soil dynamic stress gradually increase, and does not reach a constant value; however, when the cushion is set, with the increase of the loading time, pile soil dynamic stress gradually increases first and then gradually decreases; the greater the thickness of the cushion, the smaller the dynamic stress between the piles, the dynamic stress curve turns earlier. Figure 9 shows when the cushion thickness is 1m, the dynamic stress curve of the soil between piles appears the peak value, and the peak dynamic stress is the minimum. And there is a trend of reverse dynamic stress after the peak. It is also shown that the bigger the cushion thickness is, the stronger the interaction between the cushion and the pile is, but the weaker the interaction between the cushion and the soil between piles is.

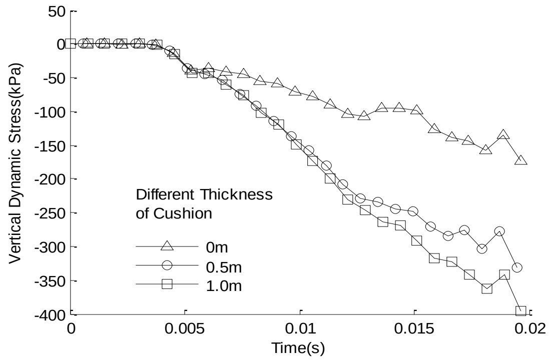

Fig. 8 - Effect of cushion thickness on dynamic stress of pile top

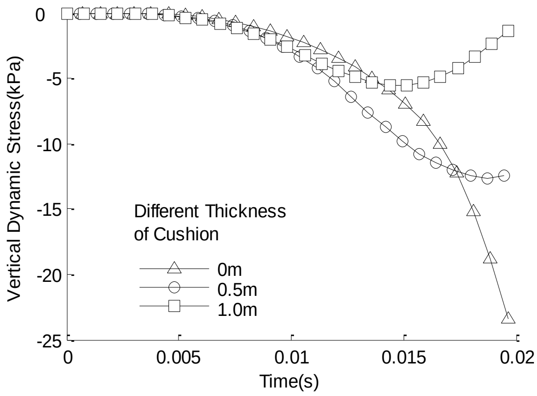

Fig. 9 - Effect of cushion thickness on dynamic stress of soil between piles

Influences of Elastic Modulus of Pile body on the Dynamic Response of CFG Pile Composite Foundation

Figure 10 respectively shows the dynamic stress curves of pile top when the elastic modulus of pile is 15GPa, 20GPa and 25GPa. Figure 11 respectively shows the variation of dynamic stress of soil between piles when the elastic modulus of pile is 15GPa, 20GPa and 25GPa. Figure 10 shows that the larger the elastic modulus of the pile, the greater the dynamic stress of the pile, but the increase amplitude of dynamic stress at the pile top by the elastic modulus will gradually decreased. Figure 11 shows that: the greater the elastic modulus of the pile, the smaller the soil dynamic stress, the soil dynamic stress curve of the pile is turning earlier; the soil dynamic stress change is small under different pile modulus changes. The smaller the elastic modulus of the pile, the smaller load the pile bears, the greater load the soil between piles bears. It is shown that the dynamic stress at pile top decreases and the dynamic stress of soil between piles increase correspondingly.

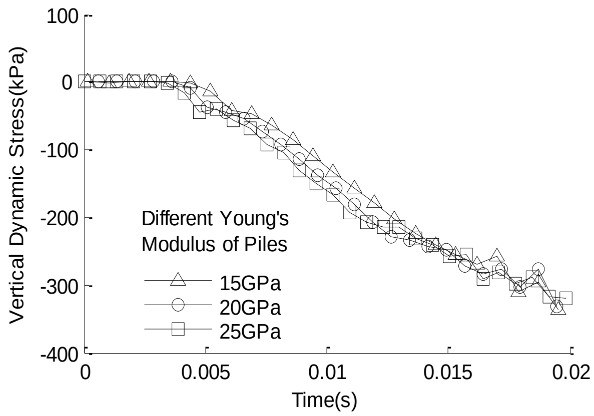

Fig. 10 - Effect of dynamic stress on pile top of pile elastic modulus

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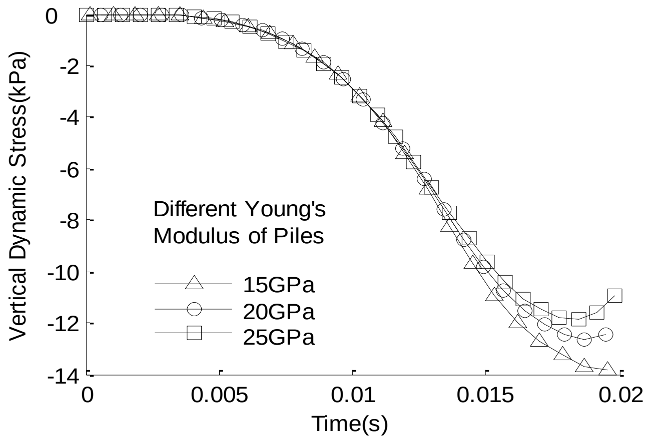

Fig. 11 - Effect of dynamic stress on soil between piles of pile elastic modulus

CONCLUSIONS

By the excitation load function corresponding to the irregularity management standard the vertical load of the train is simulated. Based on the finite difference software FLAC3D the three-dimensional dynamic coupling finite difference model of track-embankment-pile-soil composite foundation is established. The influence of different parameters on dynamic response of embankment, pile and foundation soil is analysed. The main conclusions are as follows:

(1) The dynamic stress produced by dynamic loading propagates down the embankment. After the dynamic stress passes through the cushion layer, the dynamic stress wave develops downward through the dynamic contact between the cushion and the pile and soil. Considering the great difference stiffness, the dynamic action firstly takes place between the cushion and the pile. Then, takes place between the cushion and the soil. The centre pile is mainly affected by vertical dynamic stress. Dynamic stress propagates along the embankment to side piles. The dynamic stress of the pile decreases gradually along the centre pile to the side pile.

(2)The dynamic response of the pile-soil caused by subgrade surface elastic modulus variation has little effect. With the increase of elastic modulus and thickness of cushion, the dynamic interaction between the pile and the cushion is increased while the dynamic interaction between the soil and cushion is weakened. Therefore, the bearing capacity of the pile is fully utilized.

(3)With the increase of the elastic modulus of the pile, the propagation velocity of dynamic stress in pile body is accelerated, and the dynamic stress increases gradually, but the increasing amplitude of dynamic stress decreases gradually. The pile bears most of the load. This effectively reduces the dynamic load of the foundation soil, and weakens the influence of the upper load on the composite foundation.

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