Study on Dynamic Performance of Deep-Embedded Pile-Board Subgrade in Soft Soil Area

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Abstract: Deep-embedded pile-board structure, which is implanted in foundation, changes the dynamic properties of embankment system significantly. Taking ballastless track structure into account, the system's stiffness distribution is rigid in upper and lower end and soft in middle, which increases the stress and complexity of subgrade bed. Therefore, it is necessary to specialize in the dynamic performance of low embankment on rigid foundation. Based on dynamic test system, a series of in-situ cyclic vibration tests are carried out by simulating train load in Beijing-Shanghai High-speed Railway. Dynamic response of different section and different depth is obtained and vibration characteristics and long-term dynamic properties of low embankment on rigid foundation are analyzed. The result shows that low embankment of deep-embedded pile-board structure will not resonate in train's frequency range, and dynamic response tend to be stable after 0.7 million times' vibration and displacement amplitude of each section is less than 0.1 mm. Dynamic stiffness of subgrade surface is in range of 280-350 MN/m, and the stiffness differences among sections are very small. After 1.5-2.0 million times' vibration, structure's accumulated deformation is 0.3-0.4 mm, which indicates the structure system of ballastless track, subgrade bed, pile-board structure and foundation has satisfactory long-term dynamic stability.
Keywords: rigid foundation; deep-embedded pile-board structure; dynamic performance; vibration test

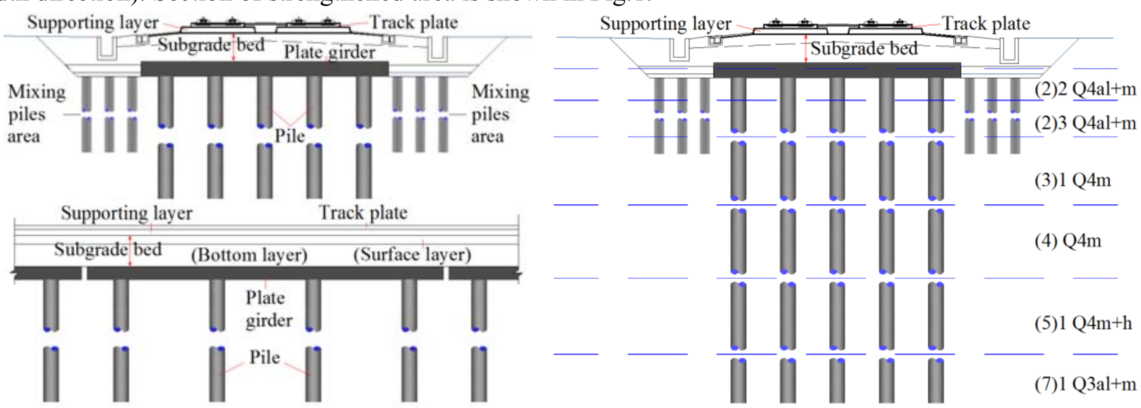
1. Introduction

In building of high-speed railway and expressway in the Yangtze River delta plain in China, challenge of super-thick soft soil has become increasingly severe[1,2], because in addition to foundation softening and permanent deformation, influence depth of dynamic loads may reach soft soil layer as train speed improving[3]. To release dynamic stress in foundation soil under train load, deep-embedded pile-board structure is first used in low embankment section of Beijing-Shanghai High-speed Railway. This structure is implanted in foundation and bears upper loads including that of subgrade bed. As a result, a stiffness distribution mode of 'rigid in upper and lower end and soft in middle' is formed. Complexity of subgrade bed's bearing state is increased since vibration wave will reflection between track plate and pile-board structure[4]. Therefore, vibration characteristics and long-term dynamic properties are the key elements of successful application of deep-embedded pile-board structure, and need to be fully investigated both theoretically and experimentally[5,6]. This study apply in-situ vibration test after the railway construction is finished, with the result comparing with that of theoretical analysis and numerical simulation.

2. Deep-embedded pile-board subgrade

Construction site of low embankment in rigid foundation in Beijing-Shanghai High-speed Railway is near Shanghai Hongqiao Station, and has a total length of 216 m. Foundation of main line is strengthened both through deep-embedded pile-board structure and preloading soil column of 2.0-3.0 m. Bored pile is used in pile-board structure, while cement mixing pile, spacing 1.2 m, is used to enhance two sides of pile-board structure with piles arranged as square. Surface layer of subgrade bed, which is 0.4 m in depth, is filled with graded gravel, while embankment and bottom layer of subgrade bed is filled with Huzhou gravelly soil, which is filler of A or B class. A 0.15 m layer of C15 concrete is set under loading plate and a 0.6 m sand cushion is arranged on top of maxing piles, and a layer of two-way high strength geogrid is laid between plate and piles. Slope of embankment is lower than 3 m with a slope ratio of 1:1.5, and is protected by breeding grass seedlings and plating bushes.

Plate girder of deep-embedded pile-board structure is below ground surface, with a distance of 1.39-1.57 m to the top of the surface layer of subgrade bed. Dimensions of plate girder are determined based on construction and bearing requirements. Thickness, length and width of C40 reinforced concrete plate girder is 0.8 m, 27m(2.5+7+8+7+2.5) and 13m(1.3+4×2.6+1.3) respectively. To decrease bend moment of side span and reduce masonry, both ends in length and width directions are set as cantilever. Diameter of bored pile is 0.8 m and its pile length is 45.5-46 m. Each unit contains 20 piles, arranging as an array of 4×5 (4 in length direction and 5 in width direction). Section of strengthened area is shown in Fig.1.



(a) Deep-embedded pile-board structure (b) Stratigraphic distribution

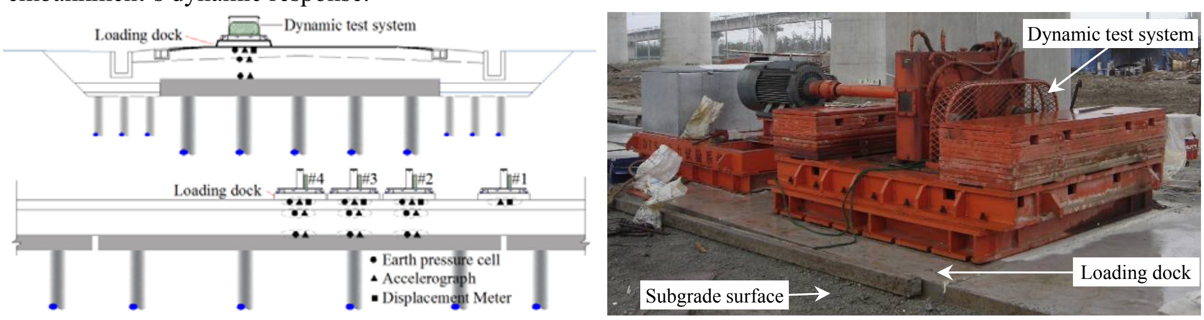
Fig.1 Schematic diagram of deep-embedded pile-board subgrade

3. Test study method

3.1. In-situ dynamic test

3.1.1. Testing scheme

Four sections are chosen to apply cyclic loading and test. As is shown in Fig. 2, these sections' distances to the top are 0m, 6m, 9.5m and 13.5m respectively. Earth pressure cell, accelerograph, displacement meter are arranged on both top and bottom of the surface of subgrade bed as well as top of plate girder to test embankment's dynamic response.



(a) Layout of instruments and load of dynamic test (b) The photo of dynamic test

Fig.2 Layout of instruments and Schematic diagram of dynamic loading test

3.1.2. Loading equipment and loading parameter

Dynamic responses of subgrade bed is tested by apply repeated impact by Dynamic Test System (DTS), which simulates the forces that running train applies on track structure. DTS is consist of vibrator, speed increaser, eccentric block, universal coupling, electrical installation, speed-up machine and cyclical cooling lubrication system, as is shown in Fig.2. Sweep frequency test and cyclic loading test were carried out respectively by adjusting mass of eccentric block and output frequency of electrical system. Main Technical Parameters in loading are as follows:

(1) Frequency

Trains loads bearing by subgrade system is one-way pulse wave and its vibration frequency is determined by train speed, vehicle distance, bogie spacing and axle spacing. It can be calculated by $f = v/(3.6 \cdot s)$(Hz). In this formula, f is frequency, v is train speed and s is distance. In specific problem, s is determined by the different parts' stress and deformation properties. For example, in conditions of investigating fatigue properties of surface layer of subgrade bed, bogie spacing is chosen to be s. When train speed is 350 km/h, dynamic frequencies of train are 38.88 Hz, 12.15 Hz and 5.40 Hz respectively. According to transfer characteristics of high-frequency waves and low-frequency waves, 5-24 Hz is chosen as sweep frequency in tests, and 20 Hz is chosen as frequency for cyclic loading.

(2) Stress Amplitude

According to the result of field tests, vertical dynamic stress's (σ_D) amplitude is between 13 kPa and 20 kPa. In this study, Stress amplitude of subgrade surface (σ_d) is adjusted to around 20 kPa by control vibration system's eccentric block (As is shown in Fig. 3).

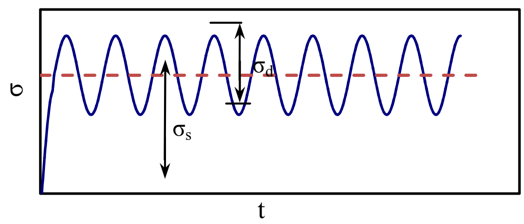


Fig.3 Simulated dynamic stresses

(3) Loading times

Based on existing research results [7,8] , cyclic loading times is setting as 1.5-2 million.

(4) Loading area

In this study, loading area is selected as 2.2m×2.2m to simulate dynamic forces of one wheel set. Vibration exciter is loading at both pile section and midspan, as the #1, #2, #3 and #4 sections shown in Fig.2.

3.2. Numerical simulation model

A 3-D model of deep-embedded embankment is built by ABAQUS software, consisting of vibration exciter, subgrade soil, plate girder, piles and foundation soil. Vibration frequency of 5 Hz, 12 Hz, 20 Hz, 28 Hz and 35 Hz are all applied on model, and three excite positions: middle of midspan, bearing of middle pile and support of side pile are chosen to compare influence of different excite position. Except dynamic stress, which uses peak-to-peak value, all other parameters (dynamic, displacement, speed and acceleration) use half peak value as dynamic response value. Basic dimensions are followed.

- Use level-3 counterweight for vibration exciter. Mass of the exciter is 13422 kg;

- eccentric block's mass is 18.14 kg and is consist of parent body and two weight (number 1 and 4);
- Thickness of soil on loading plate is 1.567 m ;
- Plate girder is made of C40 concrete with dimension of 27m×13m×0.8m;
- Piles are made of C40 concrete with diameter of 0.8m and length of 46m, arranging as an array of 4×5 (4 in length direction and 5 in width direction)

3.2.1 Build of model and choice of parameters

Based on field survey and information from related document, parameters of pile-board structure and formation are shown in Table 1.

Table 1 Parameters of deep-embedded pile-board structure model

Items	Density(kN/m^3)	Elastic Modulus (MPa)	Damping Ratio	Poisson Ratio
Vibration Exciter	7850	206000	—	0.3
Surface layer of subgrade bed	20	150	0.045	0.3
Bottom layer of subgrade bed	20	120	0.037	0.3
Plate Girder	25	34000	0.028	0.2
Pile	25	34000	0.028	0.2
Foundation Soil 1	18.6	11.25	0.03	0.37
Foundation Soil 2	17.83	10.9	0.035	0.42
Foundation Soil 3	18.6	19.59	0.035	0.42

3.2.2 Boundary treatment

When dealing with dynamic problems with finite element method, a computational domain needs to be cut out from infinite space. In edge of the severed domain, artificial boundary needs to be built to simulate radiation damping of continuous media, so that scattered wave will not reflect when pass through edge of computational domain. Dampers and springs are arranged on the artificial boundary used in this study, which can absorb energy of outgoing waves as well as realize elastic recovery function. By using this kind of boundary, accuracy of calculation is better than that of viscous boundary, and calculation instability is not likely to happen. This viscous-spring artificial boundary can be equivalent to a system of continuous distributed springs and dampers in parallel, in which stiffness factor of spring and damping factor of damper can be written as

$$K_b = a\frac{G}{R}$$

$$C_b = \rho \times c$$

In the above formula, ρ is density, G is shear modulus, R is distance from source of scattering wave to artificial boundary, c is wave speed, C_p is wave speed in normal direction and C_s is wave speed in tangential direction.

$$C_p = \sqrt{\frac{\lambda + 2G}{\rho}}\ ,\quad C_s = \sqrt{\frac{G}{\rho}}\ ,\quad G = \frac{E}{2(1+\gamma)}\ ,\quad \lambda = \frac{E\gamma}{(1+\gamma)(1-2\gamma)}$$

Value of parameter a can be chosen from Table 2. When value of a is zero or value R is infinitely great, stiffness factor K_b is zero and the viscous-spring artificial boundary turns into viscous artificial boundary.

Table 2 Value of parameter a in viscous-spring artificial boundary

Boundary Type	Direction	a
2-D boundary	Normal direction towards inside of plane	2
	Tangential direction	1.5

	Normal direction towards outside of plane	0.5
3-D boundary	Normal direction	4
	Tangential direction	2

Wang Xikang[9] indicates that under force of vibration exciter, finite model is more rational than infinite model in calculating response of embankment. In fact, dynamic response is actually very tinny out of the area influenced by exciter. The viscous-spring artificial boundary used in this study is rigorous in theory and concise expression, with favorable accuracy, stability and robustness, and has won successful application in interaction problems of dynamic machine substructure and foundation soil[10-12].

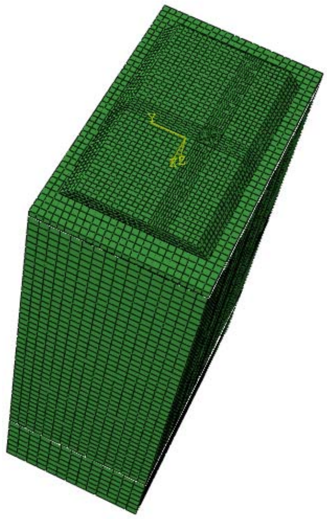


Fig.4 Numerical model of deep-embedded pile-board subgrade

4. Dynamic analysis of deep-embedded pile-board subgrade

4.1. Self-vibration property

Structure of bored pile and plate girder is forced to vibration under the effort of exciter. Its amplitude-frequency characteristic can be obtained by change frequency continuously. Amplitude is obtained through spectral analysis of dynamic deformation of test data. Since excitation force F is proportional to square of circular frequency ω^2, the amplitude should be converted to that under unit excitation force to facilitate comparison（Unit amplitude）.

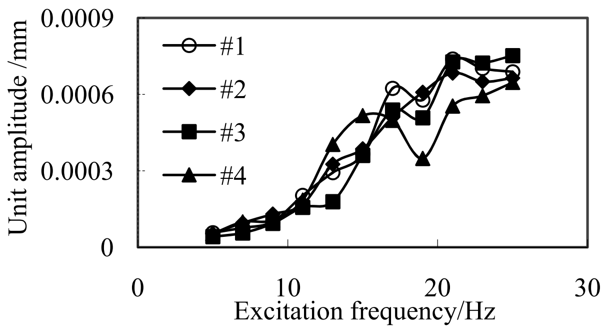
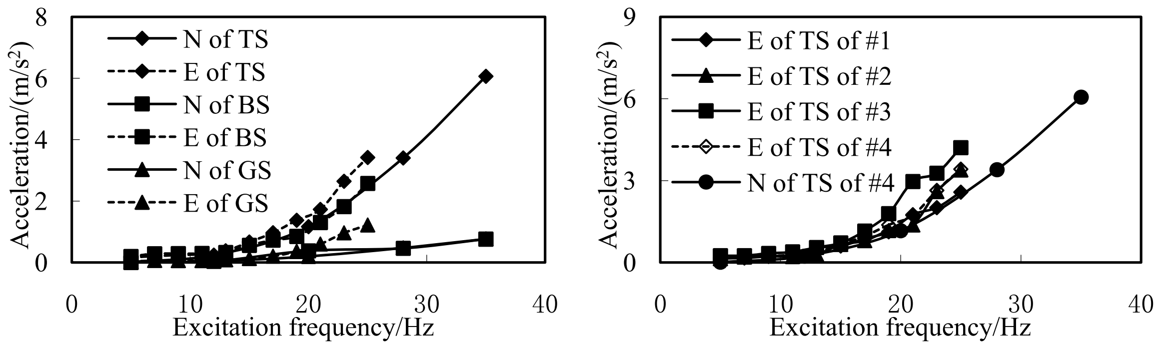


Fig.5 Amplitude-frequency characteristic curve

According to test results, natural vibration frequency of surface layer of subgrade bed is 24 Hz in minimum, and is over 30 Hz in most of the times. Amplitude of unit excitation force continues to increase as frequency increases, but does not reach peak value, which means the pile-board structure's natural vibration frequency is larger than 25 Hz. Since the testing section's bogie frequency will not exceed 25 Hz, covibration will not occur in actual operation.

4.2. Vibration response

Vibration acceleration is the main index of estimating damage effort of vibration to track structure. Its value is proportional to stiffness factor of embankment structure. Dynamic stability embankment is described by vibration acceleration varies with loading times. Through in-situ excitation test and finite element simulation, vibration characteristics of deep-embedded pile-board structure are studied. Take middle section of midspan for example. Its dynamic response is shown in the following figure.



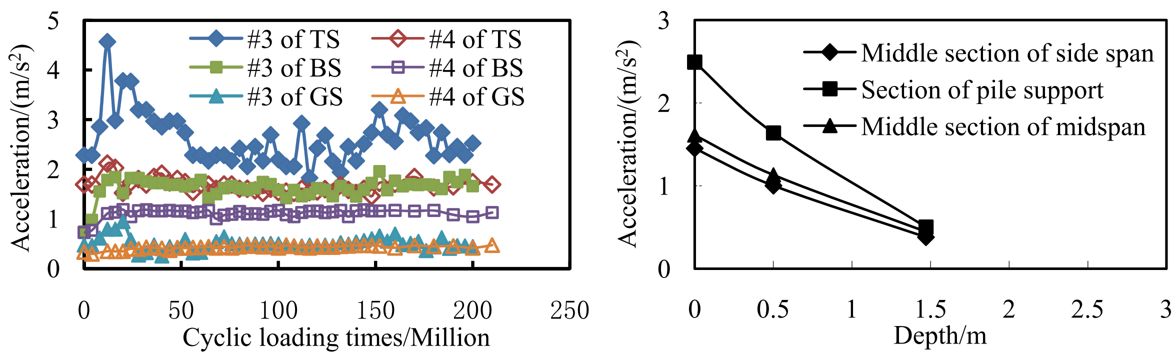
(a) Vibration response of different depth (b) Vibration response of different section

"E": Experimental value; "N": Numerical values; "TS": Top surface of surface layer of subgrade bed; "BS": Bottom surface of surface layer of subgrade bed ; "GS": Ground surface.

Fig.6 Relation curves between vibration response and forced vibration frequency

Theoretical and experimental response of vertical vibration agrees well with each other. According to data analysis, acceleration of test points is in exponential function with excitation frequency. Vibration acceleration of support section is slightly larger than those of other sections. For each section, acceleration reduces rapidly from top to bottom, from the middle to both sides. When excitation frequency is 25 Hz, which means the train speed is 450 km/h, acceleration amplitude of middle section of side span is 0.338g, acceleration amplitude of middle section of midspan is 0.342g and acceleration amplitude of support section of midspan is 0.421g. Each section's largest acceleration is less than 0.5g, which is the limit value provide by Chinese High speed railway design standard (TB10621-2009). It is safe to say, this kind of embankment structure's vibration acceleration meets the requirements of design and application.

Aiming at vibration acceleration of each layer, study is carried out by observing acceleration as loading times improves, as is shown in Fig. 7. In the beginning of loading, variation of each test point's vibration response is obvious, especially that of the surface layer in subgrade bed. After 0.7 million times' excitation, the variation tend to be stable and average amplitude of surface layer of subgrade bed, bottom layer of subgrade bed and top of plate girder are 0.19g, 0.13g, and 0.05g respectively.



(a) Time-history curve (b) Vertical distribution curve

"TS": Top surface of surface layer of subgrade bed; "BS": Bottom surface of surface layer of subgrade bed ; "GS": Ground surface.

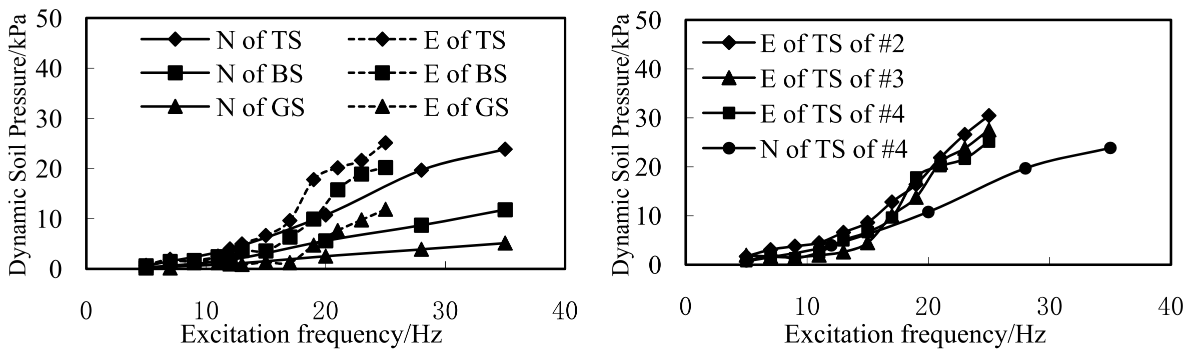
Fig.7 The acceleration of subgrade bed (20Hz)

When excitation frequency is 20 Hz, which means the train speed is 360 km/h, acceleration amplitude of middle section of side span is 0.145g, acceleration amplitude of middle section of midspan is 0.161g and acceleration amplitude of support section of midspan is 0.249g.

Acceleration of subgrade in different depth is shown in Fig. 7(b). Acceleration in section of pile support is 1.5 times of average value, due to its larger stiffness. Otherness and variation are both get smaller as depth improves. Distribution of acceleration is an inverted triangle, since acceleration decays very quickly as dynamic wave of train loads transmits downwards. On top of plate girder, 1.47 m under surface of subgrade bed, acceleration decreases to a quarter of that of subgrade bed surface. The attenuation coefficient is good agreement with theoretical value.

4.3. Dynamic soil pressure

Dynamic soil pressure of embankment decreases as depth increases and vibration wave transmits. This phenomenon is caused by geometry attenuation and physics attenuation, both of which are strongly influenced by shear modulus, Poisson ratio and stratification of different soil. Dynamic soil pressure inflects the effect that train load applies on subgrade, and distribution of dynamic soil pressure is closely related to transmission mechanism of dynamic stress in soil. Different excitation frequency, loading times are applied during loading test to investigate the stability of dynamic stress transmission coefficient. Only the soils in areas on top of plate girder are tested in this study, as is shown in Fig. 8.



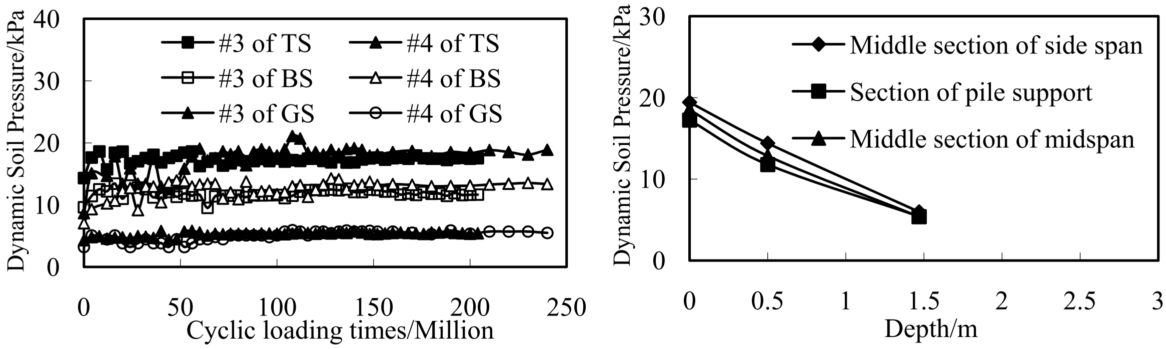
(a) Dynamic soil pressure of different depth (b) Dynamic soil pressure of different section

"E": experimental value; "N": Numerical values; "TS": Top surface of surface layer of subgrade bed; "BS": Bottom surface of surface layer of subgrade bed ; "GS": Ground surface.

Fig.8 Relation curves between dynamic soil pressure and forced vibration frequency

Dynamic soil pressure of test points is in exponential function with excitation frequency. When excitation frequency is 25 Hz, which means the train speed is 450 km/h, dynamic soil pressure amplitude of middle section of side span is 30.462 kPa, dynamic soil pressure amplitude of middle section of midspan is 25.148 kPa and dynamic soil pressure amplitude of support section of midspan is 27.549 kPa.

Time-history curves of dynamic soil pressure are shown in Fig.9 (a). In the beginning of loading, dynamic soil pressure experiences a period of obverse variation, which is caused by adjustment and coupling between soils and transducers. After 0.7 million times' excitation, the variation tends to be stable. When excitation frequency is 20 Hz, which means the train speed is 360 km/h, dynamic soil pressure is in range of 17-20 kPa. By averaging each points' stable value, vertical attenuation of each sections' dynamic soil pressure can be analyzed, as is shown in Fig. 9.



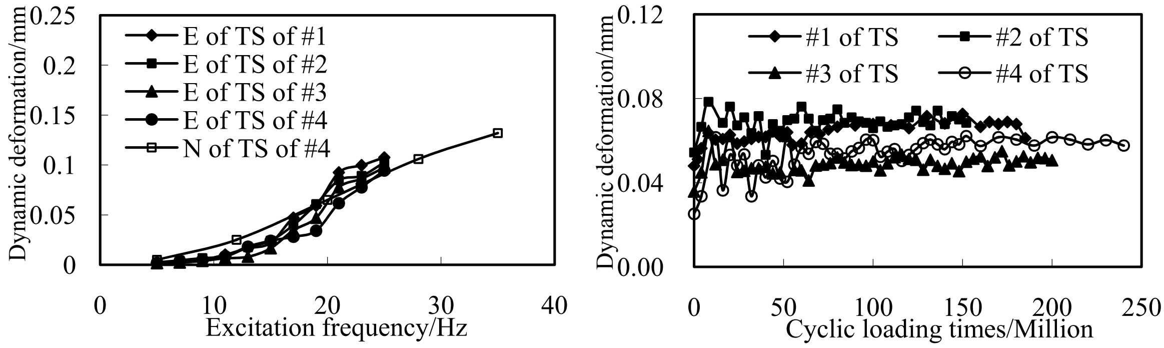
(a) Time-history curve (b) Vertical distribution curve

Fig.9 The dynamic soil pressure of subgrade bed

Dynamic soil pressure decays linearly in depth. Distribution of dynamic soil pressure is also an inverted triangle and also decreases very fast from top to bottom. Pressure of support section is slightly larger than those of other sections. On the position 0.5 m under the surface layer of subgrade bed, dynamic soil pressure decreases to 70.6% of that of subgrade bed surface, while on top of plate girder, 1.47 m under surface of subgrade bed, dynamic soil pressure decreases to 30.4%. The attenuation coefficient is good agreement with theoretical value.

4.4. Dynamic deformation

A rigid foundation for track structure must by provided so that high-speed train will have a smooth running condition. Dynamic deformation of subgrade surface under train effect is a significant index of subgrade. As to deep-embedded pile-board embankment, dynamic deformation mainly takes place in the surface layer of subgrade bed, and will finally reflect on deformation of track surface. It can directly worsen interaction and vibration of track system and vehicles, and threaten high-speed railway's safety and comfort. Aiming at dynamic deformations of excitation points, vibration situation of each section under different loading times is shown in Fig. 10.



(a) Relation curves of different section (b) Time-history curve of different section

Fig.10 Dynamic deformation of subgrade surface

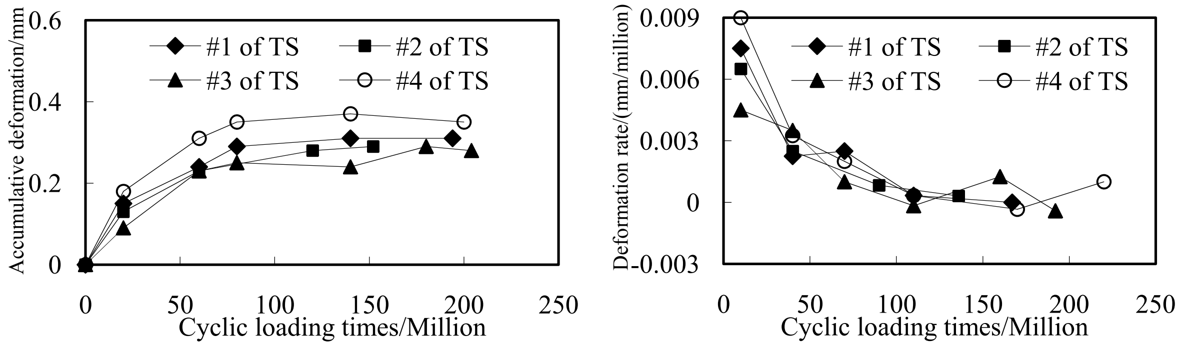
According to test data, dynamic deformation of test points is in exponential function with excitation frequency, and decays relatively fast along longitudinal direction of track. When excitation frequency is 25 Hz, which means the train speed is 450 km/h, dynamic deformation amplitude of cantilever is 0.108 mm, dynamic deformation amplitude in middle section of side span is 0.103 mm, dynamic deformation amplitude in middle section of midspan is 0.095 mm and dynamic deformation amplitude in support section of midspan is 0.098 mm.

All the sections' largest dynamic deformations are less than 0.2 mm, while 1 mm is the most accepted limit value of dynamic deformation at present.

Time-history curves of dynamic deformation are shown in Fig. 10(b). In the beginning of loading, value of dynamic deformation experiences a period of obverse variation, which is caused by adjustment and coupling between soils and transducers. After 0.7 million times' excitation, the variation tends to be stable and all test points' dynamic deformations are less than 0.1 mm, with very small difference between sections. When excitation frequency is 20 Hz, which means the train speed is 360 km/h, dynamic deformation amplitude of cantilever is 0.066 mm, dynamic deformation amplitude in middle section of side span is 0.070 mm, dynamic deformation amplitude in middle section of midspan is 0.057 mm and dynamic deformation amplitude in support section of midspan is 0.050 mm.

4.5. Accumulative deformation

Accumulative deformation mainly takes place in subgrade bed and influences track system's geometric smooth directly. Great accumulative deformation of subgrade bed implies not only huge repair quantity but also danger of insufficient capability. In building of new line, filling material, E_{vd}, K_{30} are all strictly controlled to reduce accumulative deformation. However, fatigue failure of subgrade bed or oversized accumulative deformation happens in long-term accumulation rather in short-term running. So, aiming at permanent deformation in excitation position, study is carried out by observing accumulative deformation of each section as loading times improves, as is shown in Fig. 11.



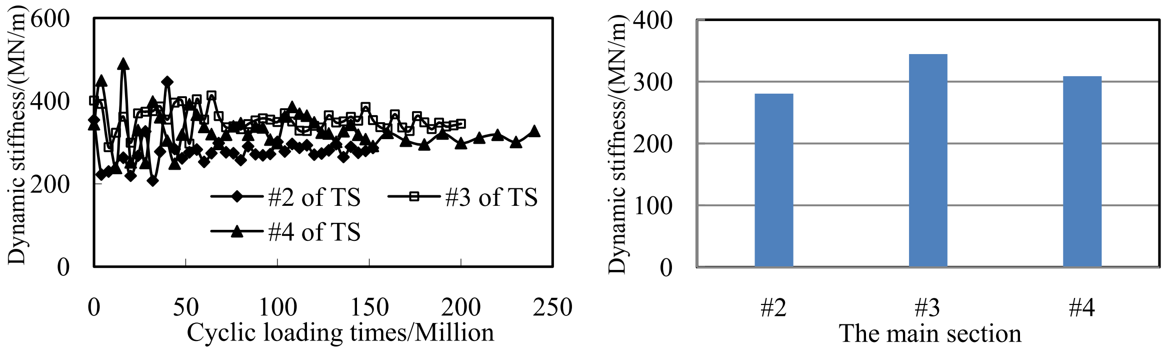
(a) Time-history curve of accumulative deformation (b) Time-history curve of rate of accumulative deformation

Fig.11 The accumulative deformation of subgrade surface

Deformation accumulation deceases as loading times increases and finally reaches a stable state after 0.7 million times' vibration, indicating that accumulative deformation will be efficiently controlled as long as dynamic stress of subgrade bed is less than threshold value. Final deformation of deep-embedded low embankment is 0.3-0.4 mm, which is very small because of the great improvement of foundation capability provided by pile-board structure.

4.6. Comprehensive dynamic stiffness

Comprehensive dynamic stiffness reflects the ability of embankment resisting dynamic deformation. It is the performance of pile-board structure system's stiffness of each part and has important connection with stability of track system and comfort of train running. Comprehensive dynamic stiffness can be calculated by dynamic response curve of system's dynamic stress and deformation. The system is coupled of dynamic test machine system and pile-board structure system. When forced vibration of this system reaches stable state, dynamic stiffness can be described as $K_d=\sigma_{max}/s_p$, in which σ_{max} is peak value of dynamic stress and s_p is its corresponding dynamic deformation. Comprehensive dynamic stiffness of deep-embedded low embankment under different loading times is shown in Fig. 12(a). Dynamic stiffness of different sections of deep-embedded low embankment is shown in Fig. 12(b).



(a) Time-history curve of dynamic stiffness (b) Dynamic stiffness of different section

Fig.12 The dynamic stiffness of subgrade surface

Dynamic stiffness decreases as excitation frequency increases, and gets basically stable when frequency reaches 10 Hz. Value of embankment's dynamic stiffness is larger than 260 MN/m under any frequency. In the beginning of loading, variation of each test point's dynamic stiffness is obvious, and after 0.7 million times' excitation, dynamic stiffness tends to be stable. When excitation frequency is 20 Hz, which means the train speed is 360 km/h, dynamic stiffness of middle section of side span is 280.302 MN/m, dynamic stiffness of middle section of midspan is 324.981 MN/m and dynamic stiffness of support section of midspan is 347.520 MN/m. Wang Bing-long [13] indicates that properties of embankment material will be changed in rain weather and dynamic stiffness will reduce significantly. During this study, rain weather occurred repeatedly. Since embankment was not protected from water, filling material was in saturated condition during testing, so the test result is less than actually value. Anyway, this embankment's dynamic stiffness is undoubtedly sufficient. Another superiority of this structure's stiffness properties is that since pile-board structure is embedded 1.47 m under surface of subgrade bed, uneven stiffness on top of plate girder will not be reflected obviously on subgrade surface.

4.7. Transfer law of dynamic loads

In traditional embankment, dynamic loads are simply transferred from top to bottom. With more complicated constitution, pile-board structure's transfer law of dynamic loads was in urgent need of been understood. Based on soil pressures of four excitation sections, dynamic load is still transfer from top to bottom on embankment soil above plate girder. Under the diffusion effect of 1.5 meter's soil, around 30% of the total dynamic stress will be transferred to the pile-board structure blow.

According to results of excitation test, the decayed stress that reaches pile-board structure is first transferred to plate girder, causing deformation and vibration, and then most of it goes to piles while others goes to soil. Under effect of upper dynamic loads, piles experience compression deformation and vibration, and transfer dynamic stress to deeper soil. Soil between piles plays a significant rule in absorb dynamic stress from piles.

5. Conclusions

Through dynamic test of pile-board structure in high-speed railway, some conclusions about stress, deformation and vibration characteristics of this new embankment structure can be drawn as follows.

(1) Pile-board structure's natural vibration frequency is larger than 25 Hz, while high-speed railway's bogie frequency is less than 25 Hz. Covibration of vehicle and embankment will not occur in actual operation.

(2) As depth improves, both vibration acceleration and dynamic stress have a distribution of inverted triangle. Vibration waves decay very quickly as transmitting downwards, with only around 30% of subgrade surface value remains on top of plate girder. After 0.7 million times' vibration, both vibration acceleration and dynamic stress tend to be stable. Vibration response of support section is slightly larger than those of other sections.

(3) Accumulative deformation and dynamic deformation develop simultaneously, both of which get stable after 0.7 million times' vibrations. Dynamic deformation of each section is less than 0.1 mm, while accumulative deformation is between 0.3-0.4 mm. After dynamic deformation reach stable state, embankment system is in elastic state under dynamic load and accumulative deformation stops further development.

(4) Dynamic stiffness decreases as excitation frequency increases, and gets basically stable when frequency reaches 10 Hz. Value of embankment's dynamic stiffness is larger than 260 MN/m under any frequency. When excitation frequency is 20 Hz, dynamic stiffness of sections are between 280-350 MN/m with stiffness differences less than 15%, indicating that structure has good smoothness.

(5) Dynamic stress produced by exciter is decayed by embankment soil before reaching pile-board structure, and then transferred to plate girder, causing deformation and vibration, and then most of it goes to piles while others goes to soil. Under effect of upper dynamic loads, piles experience compression deformation and vibration, and transfer dynamic stress to deeper soil. Soil between piles plays a significant rule in absorb dynamic stress from piles.

No matter in controlling deformation or maintaining smoothness, the structure system of ballastless track, subgrade bed, pile-board structure and foundation has satisfactory long-term dynamic stability and can well meets the requirements of high-speed railway.

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