Dynamic Analysis of Train-Bridge Systems in High-Speed Railway Bridges Considering Soil-Pile Interaction in Soft Soil Environment

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Abstract - **Over the past decade, the development of high-speed railways in China has gained worldwide attention. With the speeding up of the running train, the coupling vibration of the train-bridge system is aggravated, especially for railways built in a soft soil environment. In this paper, the dynamic features of the train-bridge system when considering and failing to consider pile-soil interaction are investigated, i.e., the "train-bridge-pier-pile-soil" (TBPPS) and "train-bridge-pier" (TBP) models. The study is based on a practical high-speed railway project in Hainan Province, where a 32 m span simply-supported box girder bridge with a four-shaft locomotive using two-system suspension model is studied. Results indicate that the natural frequency of the bridge is obviously reduced when the pile-soil interaction is considered, and the vertical vibration frequency of the bridge girder is increased from 4.87 Hz to 5.46 Hz. Moreover, the resonance speed is 500 km/h both for TBP and TBPPS. The results of bridge dynamic load factors, wheel load reduction rates, and train vibration acceleration are significantly different for TBP and TBPPS, and it is not safe if the pile-soil interaction is not considered. Therefore, it is recommended that the pile-soil interaction is extremely important for the train-bridge system when evaluating the safety and smoothness of train running. If the pile-soil interaction is not involved, the derivation will be significantly large.**

Keywords - the train-bridge system, pile-soil interaction, high-speed trains, dynamic load factors, wheel load reduction rates, resonance speed

I. INTRODUCTION

Over the past decade, the development of the high-speed railway in China has gained worldwide attention. Nowadays, it is increasingly significant to ensure the operation safety of the high-speed railway and its infrastructures. Train-bridge interaction is a critical technical issue during the operation of the high-speed railway [1-2]. A wide range of studies have indicated that the irregularity of the road route, the settlement of the foundation and the long-term deformation of the bridge will have a significant impact on the running stability of the high-speed train and the comfort of the passengers [3-6]. Hence, the establishment of an accurate train-bridge interaction model is an essential task for analysing the comfort and operation safety of high-speed trains.

In the conventional train-bridge coupling research, the constraint of bridge piers to the superstructure is generally simplified as a support bearing [1,5], and in doing so we find that the influence of the foundation soil on the dynamic behaviour of the train-bridge coupling system is actually ignored. However, in reality, pile-soil interaction elastically constrains the bridge superstructure, which definitely affects the vibration behaviour of the train-bridge system. This issue gradually receives more attention in recent years [7]. First established an analytical model of the "train-bridge-pier-pile-soil" coupling system, and reported that there are more significant deviations of the lateral vibration responses of bridges considering pile-soil interaction than that using the conventional "train-bridge" coupling system, especially in the soft soil environment [8]. Simplified the bridge pile foundation into an elastic foundation beam, and simulated the dynamic features of the soil using the spring and the damper to study the coupled vibration behaviour of the train-bridge system. Their study indicated that the soil-structure interaction should be included in the dynamic analysis of the train-bridge system. [9] established the bridge finite element model with the pile foundation of a continuous rigid frame high-speed railway bridge, and the effect of the pile-soil interaction on the vibration of the train-bridge system is obtained. [10] built the pile-soil nonlinear interaction model by utilizing the modified P-Y curve method and the load transfer hyperbolic method in line with Winkler's foundation beam theory. It was found that when the lateral displacement of the bridge increases, the vertical displacement increases, and the bridge acceleration amplitude decreases when the pile-soil nonlinear interaction was considered. In summary, the pile-soil interaction exerts a significant influence on the coupled vibration of train-bridge systems, which should be taken into account in the dynamic analysis of high-speed railway bridges.

This paper focuses on a practical high-speed railway project located in Hainan Province, where the regional soil environment is famous for its soft soil, and the builders wonder whether the soil environment affects the speed of the train. Based on geological parameters of the soft soil in this area, this paper established two coupled vibration

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models, with one involving soil-pile interaction and the other not, which are termed as ‘vehicle-bridge-pier-pile-soil’ and ‘vehicle-bridge-pier’ models. The two coupled vibration models are then used and compared to analyse the impact of pile-soil interaction on train-bridge coupling vibration behaviour. Firstly, the mechanical models of the train, the bridge, and the pile-soil interaction are established, and the analytical method of the train-bridge system is given. Then, the influence of pile-soil interaction on the natural vibration characteristics of the train-bridge system is investigated. Finally, a series of parameters, including the dynamic load coefficient, the wheel load reduction rate and vehicle body vibration acceleration, are investigated in consideration of different driving speeds and pile-soil interaction.

II. FUNDAMENTAL ANALYTICAL MODELS

A. The bridge

In the analysis, the bridge is modelled using spatial beam elements. The following assumptions are used in the modelling: (a) The track is simplified as a part of the bridge deck, and there is no relative slip between the track and the bridge deck; (b) The deformation of the cross-section of the bridge is overlooked thanks to the large longitudinal stiffness of the cross-section; (c) The bridge piers and girders are modelled by means of beam elements with an equal cross-section and the torsional moment of inertia being considered.

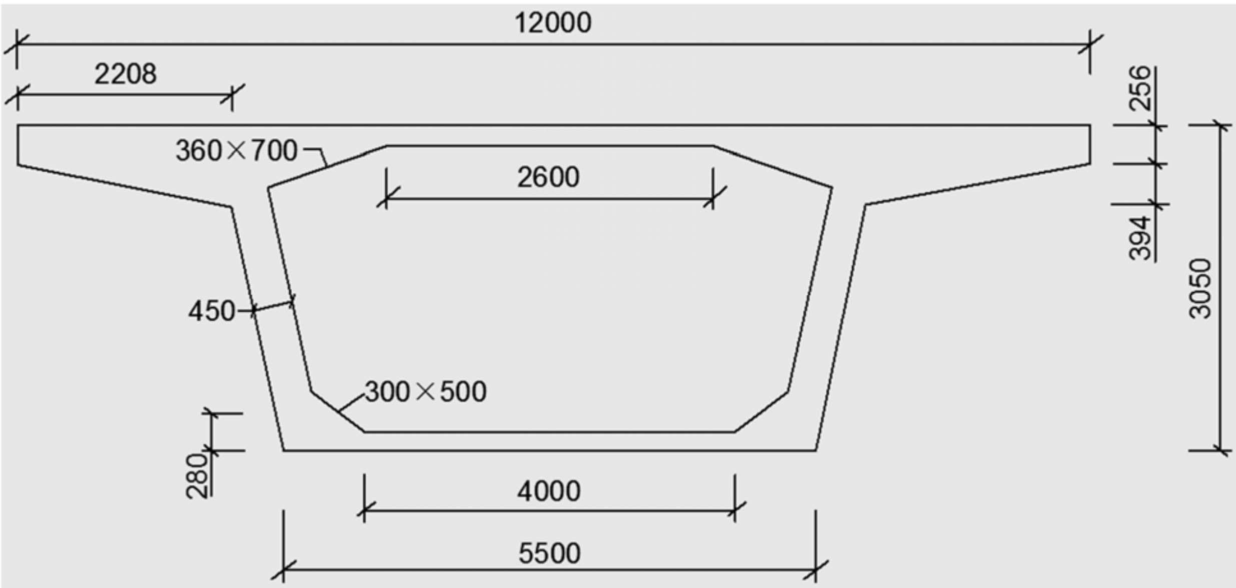

Fig. 1. The layout of the cross section of the girder bridge

A typical simply-supported girder bridge is utilized for the analysis. The span length of the bridge is 32 m. C30 concrete is used for the bridge girder and piers, and plate rubber bearings are used. The foundation of the bridge uses a clump of piles and C30 concrete cast-in-place. The length of a single pile is 14 m, and the diameter is 1000 mm. The size of the cross-section of the box girder is shown in Fig. 1.

B. The High-Speed Train

The four-shaft locomotive and the six-shaft locomotive are commonly used high-speed trains in China. In the paper, the four-shaft locomotive is utilized for analysis. A representative four-shaft locomotive contains one train body, two bogies, and four pairs of wheelsets, i.e., seven rigid bodies. For each rigid body, five degrees of freedom, which are vertical displacement, lateral runout, rolling, nodding and shaking should be considered. In summary, there are 35 degrees of freedom for a four-shaft locomotive.

In the paper, the Chinese power centralized high-speed train is selected as the train model consisting of 8 sections. In the train model, the two-system suspension models are applied, and the relevant parameters are shown in Table I. Fig. 2 shows the four-shaft locomotive using two-system suspension models.

TABLE I. CALCULATION PARAMETERS FOR THE HIGH-SPEED TRAIN MODEL

Parameters	Unit	Value	
		tractor	trailer
Length, Ln	m	26.570	26.570
Clear gap, D	m	17.375	17.375
Axle spacing, Lb	m	2.500	2.500
Mass, M	t	63.800	47.400
Bogie mass, m1	t	4.297	3.500
Wheelset mass, m2	t	1.900	1.400
First-layer spring stiffness, K1	kN/m	2340	550
First-layer damping coefficient, C1	kN.s/m	21	12
Second-layer spring stiffness, K2	kN/m	886	400
Second-layer damping coefficient, C2	kN.s/m	64	80

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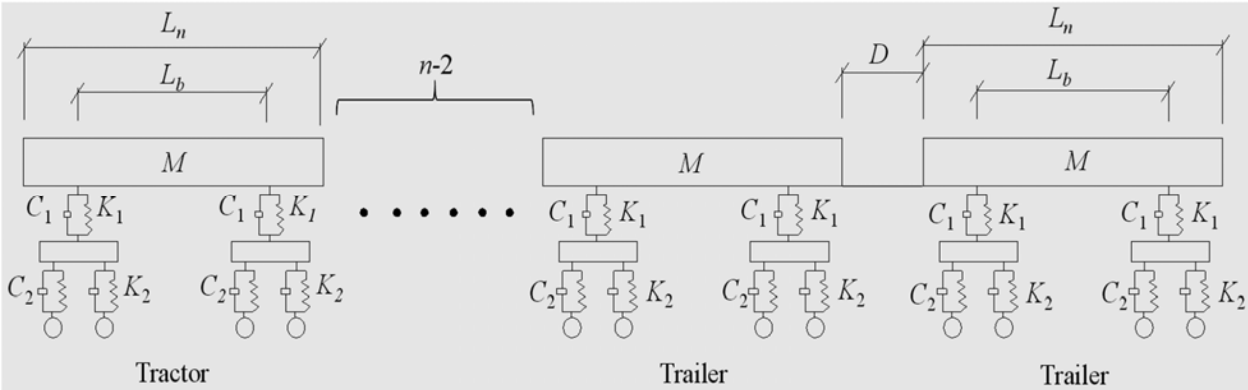

Fig. 2. The layout of the high-speed train model

C. The Pile-Soil Interaction Model

The pile-soil interaction model is illustrated in Fig. 3. The calculation of the pile-soil interaction is performed via using the m method, which is further explained in the following part. When the pile-soil interaction is not considered, a fixed constraint is used at the bottom of the bridge piers.

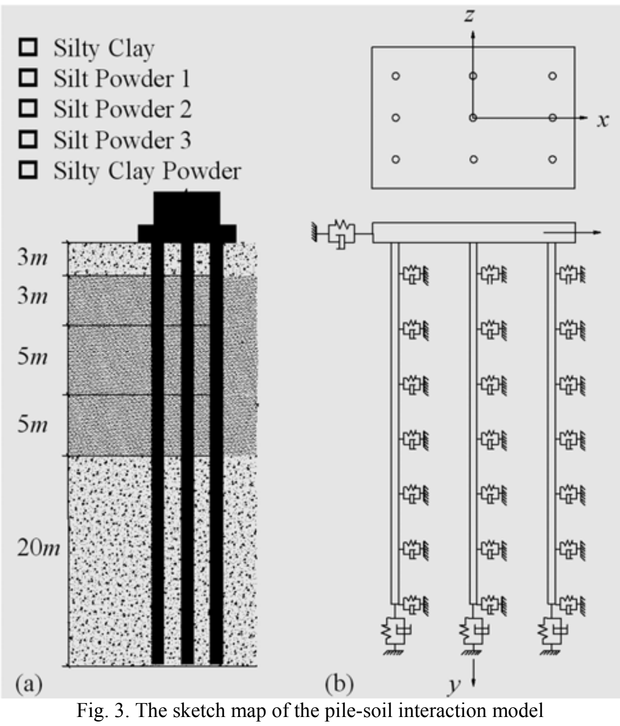

Fig. 3. The sketch map of the pile-soil interaction model

Using the m method, we find that the piles are meshed as beam elements. Equivalent soil springs are used to model the interaction between the piles and the soil, and the spring stiffness is computed by the following formula.

The stiffness of the horizontal spring to the pile is calculated by:

$$K_h = m(y) \cdot b \cdot y \qquad (1)$$

where b is the calculative width of the pile. Besides, y is the vertical distance between the calculated point and the ground; m is the proportional coefficient of the horizontal resistance coefficient of a non-rock foundation.

The stiffness of the vertical spring to the pile is calculated by

$$K_v = \frac{1}{2\Delta l} \cdot u \cdot q_{ik} \cdot l_i \qquad (2)$$

where Δl is the relative slippage between the pile and the soil for friction piles that is generally 6 mm from engineering practice. qik is the standard value of the soil friction around the pile; li is the thickness of the soil; u is the circumference of the pile.

The vertical stiffness of the pile in the bottom is calculated by

$$K = A_i \cdot m(y) \cdot y \qquad (3)$$

where Ai is the area of the cross-section of a single pile.

Owing to the fact that the overburden depth of the pile bottom and the horizontal stiffness of the soil to the pile are significant, the displacement of the pile bottom is generally very slight. This means that the pile bottom can be assumed to be fixed, and the calculation results will not be greatly affected. The soil distribution for the bridge is shown in Fig. 3 (a), and relevant soil parameters are reflected in Table II.

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TABLE II. THE SOIL PARAMETERS IN THE PILE-SOIL INTERACTION MODEL

Number	Thickness (m)	Soil type	Average m value (kN/m4)	Frictional resistance (kpa)	Stiffness of the vertical spring (kN/m)	Stiffness of the horizontal spring (kN/m)
1	3.0	Silty clay	5812	73	52529	47080
2	3.0	Silt powder 1	5812	57	44745	141231
3	5.0	Silt powder 2	5812	69	90275	444618
4	5.0	Silt powder 3	5812	41	34867	706158
5	20.0	Silty clay powder	/	/	63874	/

D. The Analytical Framework

With the bridge, the train, and the pile-soil interaction models, the train-bridge system could be analysed by solving the system dynamic equation. In general, the motion equation of the entire "train-bridge-pier-pile-soil" system could be decomposed into two independent equations, i.e., the train vibration equation and the bridge vibration equation which are expressed as the two following independent equations, respectively.

$$[M_T]\left\{\ddot{X}_T\right\}+[C_T]\left\{\dot{X}_T\right\}+[K_T]\left\{X_T\right\}=\{F_{TG}\}+\{f_T\} \quad (4)$$

$$[M_B]\left\{\ddot{X}_B\right\}+[C_B]\left\{\dot{X}_B\right\}+[K_B]\left\{X_B\right\}=\{F_{BG}\}+\{f_B\} \quad (5)$$

The subscripts T and B denote the train and the bridge, respectively. $\{X_T\}$ is the displacement vector of the train. $[M_T], [C_T],\ and\ [K_T]$ are the mass matric, the damping matrix, and the stiffness matrix of the train. $\{X_B\}$ is the displacement vector of the bridge. $[M_B], [C_B],\ and\ [K_B]$ are the mass matric, the damping matrix, and the stiffness matrix of the bridge. $\{F_{VG}\}$ is the force acting on the train and it is independent of the motion of the train on the bridge. $\{F_{BG}\}$ is the force acting on the bridge and is independent of the motion of the train on the bridge. $\{f_v\}$ is the force acting on the train and is merely associated with the motion of the train. $\{f_B\}$ is the force acting on the bridge and is bound up with the motion of the train and the bridge.

Let us assume that the wheelsets and the train tracks are always in contact, and the geometric compatibility condition and the static equilibrium condition between the wheelsets and the train track are satisfied at the contact points. The following equations are therefore derived.

$$x_T = x_B + y_s \quad (6)$$

$$f_{TB} = f_{BT} = f_n \quad (7)$$

ys is the displacement vector induced by track irregularity. fBT is the force acting on the train by the bridge. fBT is the force acting on the bridge by the train. fn is the normal contact force between the wheelsets and the train track.

Combining equations (4) with (7), we find that the entire train-bridge system is achieved. With the solution of these equations, the vibration results of the train and the bridge are acquired. In the paper, the commercial software LUSAS is used to calculate the normal contact force between the wheelsets and the train track. Then, the vibration results of the entire train-bridge system are achieved. The finite element model of the "train-bridge-pier-pile-soil" system using LUSAS is shown in Fig. 4.

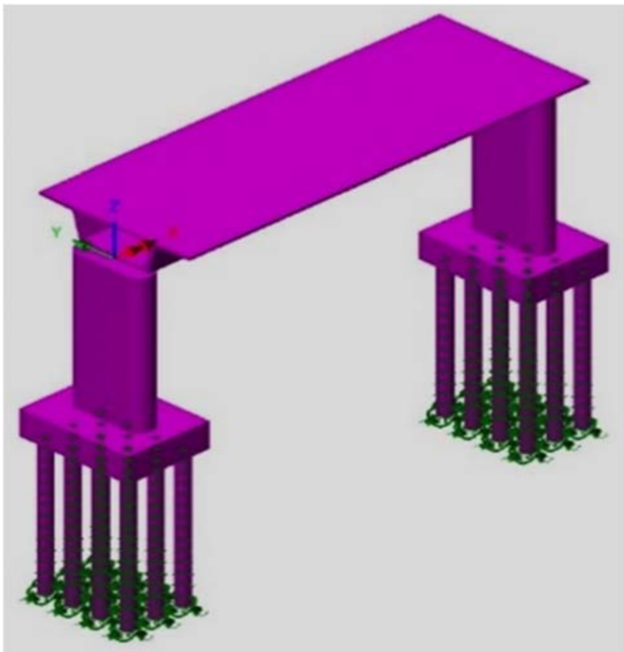


Fig. 4. The finite element model of the "train-bridge-pier-pile-soil" system

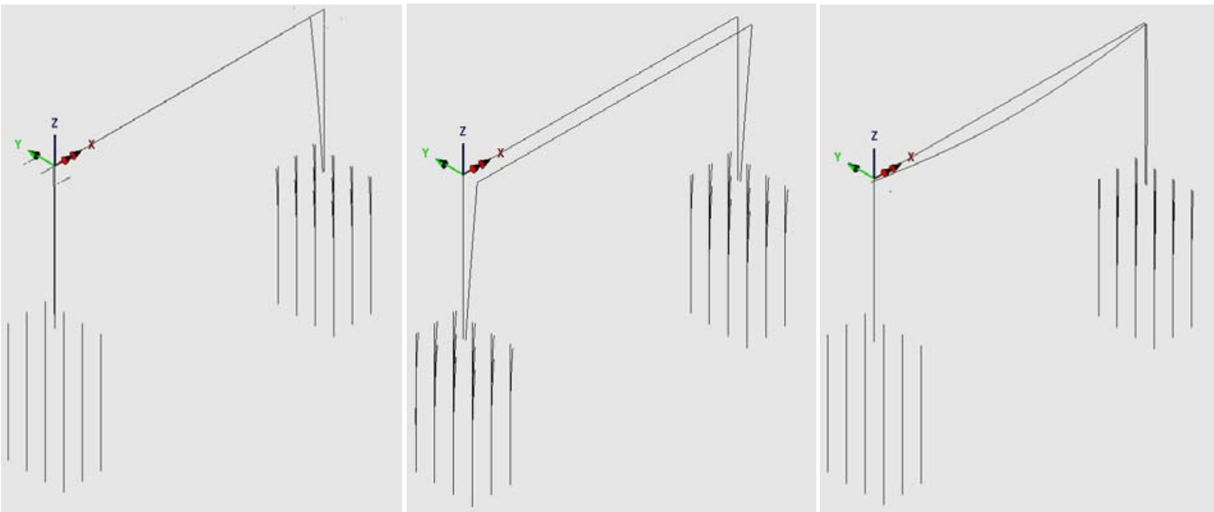
III. THE EFFECT OF PILE-SOIL INTERACTION ON BRIDGE DYNAMIC CHARACTERISTICS

In this section, two train-bridge models are established to study the impact of pile-soil interaction on the vibration features of the train-bridge system, which are "train-bridge-pier" (TBP) and "train-bridge-pier-pile-soil" (TBPPS) models. The natural frequencies calculated by these two models are analyzed and compared as shown in Figs. 5 and 6 and Table III.

Table III shows the natural frequencies and vibration modes of the two sorts of models. It is known that when the pile-soil interaction is considered, the natural vibration traits of the bridge vary eminently. The deformation of the pile foundation and the soil reduces the corresponding frequencies of each mode order, and the vertical mode of the bridge girder appears from the first order to the third order. The vertical vibration frequency of the bridge girder is reduced from 5.46Hz to 4.87 Hz when the pile-soil interaction is neglected, which will have a great impact on the vertical vibration of the bridge structure. In consequence, the pile-soil interaction should be taken into consideration in the vibration analysis of the train-bridge system.

(a) The first order mode (b) The second order mode (c) The third order mode

Fig. 5. The first three order modes of the TBP model



(a) The first order mode (b) The second order mode (c) The third order mode

Fig. 6. The first three order modes of the TBPPS model

TABLE III. NATURAL FREQUENCIES AND VIBRATION MODES BETWEEN TBP AND TBPPS

Mode order	TBP		TBPPS	
	Frequency (Hz)	**Vibration mode**	**Frequency (Hz)**	**Vibration mode**
1	2.01	Longitudinal	0.99	Longitudinal
2	5.46	Vertical	1.59	Transverse
3	6.85	Transverse	4.87	Vertical

IV. THE EFFECT OF SPEED ON THE VIBRATION OF THE TRAIN-BRIDGE SYSTEM

A. Resonance Behavior

When a train passes through a simply-supported girder bridge at the speed of V, the train could be simplified as a periodic load with a frequency of fv=V/Lt, where Lt is the total length of the train. When the excitation frequency is a multiple time of the natural vibration frequency of the bridge, the resonance phenomenon will occur, and the

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bridge vibration response is the most significant one. Hence, the resonance speed corresponding to the bridge is

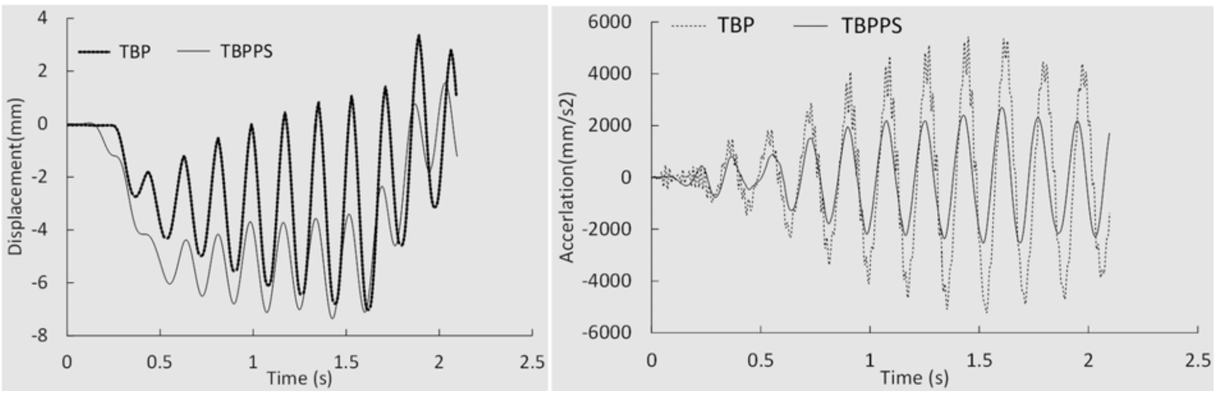
$$V_i = f_b \cdot \frac{L_t}{i}, i = 1,2,3.... \quad (8)$$

The natural vertical frequency of the simply-supported girder bridge is 4.87 Hz in view of pile-soil interaction. In China, the length of a section of a train is 27.5 m. Therefore, the resonance speed of the train is V=3.6×4.87×27.5/1=482 km/h. Table IV gives the dynamic responses of the bridge under different train speeds. The results indicate that the vertical displacement and acceleration of the bridge under TBP and TBPPS alter in a similar way with the increase of train speed. When the train speed is close to 500 km/h, the bridge responses most significantly, signifying that the resonance speed is in accordance with the calculated resonant speed.

TABLE IV. DYNAMIC RESPONSE OF THE BRIDGE UNDER DIFFERENT TRAIN SPEEDS

Speed (km/h)	TBP		TBPPS	
	Displacement (mm)	Acceleration (mm/s2)	Displacemen t (mm)	Acceleration (mm/s2)
150	3.58	696	5.96	658
200	3.40	705	6.11	605
250	3.43	619	6.07	505
300	3.73	1267	6.39	800
350	4.11	1276	6.62	948
400	4.14	1487	6.11	1082
450	4.62	2638	6.41	1189
500	6.98	5453	7.39	2744
550	5.85	4685	6.78	2056
600	4.51	3151	6.34	1871

The results also reveal that the mid-span vertical acceleration of the TBPPS is normally smaller than that of the TBP, especially when the resonance speed is reached. The peak value of mid-span vertical acceleration of the bridge between TBP and TBPPS is markedly disparate. This is because the vertical stiffness of the train-bridge system decreases after considering the pile-soil interaction, and the intensity of the vertical vibration of the bridge slows down under the exact external load.



(a) vertical displacement (b) acceleration

Fig. 7. The dynamic bridge responses in the middle span when the train speed is 500km/h

B. The Bridge Dynamic Load Factor

The dynamic load factor is a key coefficient to represent the dynamic behavior of the bridge. In the paper, the dynamic load factor is defined as the ratio of the maximum dynamic deflection to the maximum static deflection that occurs when the train crosses the bridge.

$$\mu = \frac{Y_d - Y_s}{Y_s} \quad (9)$$

Yd and Ys are the maximum deflection and the maximum static deflection when the train crosses the bridge, respectively.

Fig. 8 gives the dynamic load factors of the bridge girder under various train speeds. The results show that the dynamic load factor increases with the increase of train speed, and reaches the maximum when the train speed comes to the resonance speed. The differences of dynamic load factors between TBP and TBPS are small when the train speed is below 350 km/h, but are then significantly large especially when the train speed reaches the resonance speed. The dynamic load factor of the TBPPS model lies between 0 and 0.3. Nevertheless, the results using the TBP model come to a rather significant maximum value of 0.89. Therefore, the train-bridge system should consider the pile-soil effect so that the dynamic behavior of the bridge is accurately calculated. To reduce the dynamic responses of the bridge girder, it is recommended to set an upper bound speed for the operation of the high-speed train.

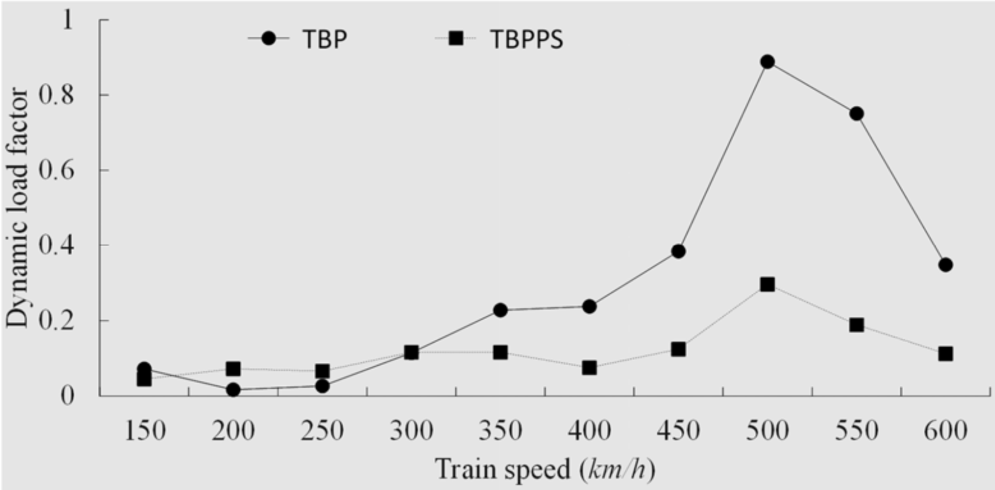


Fig. 8. The dynamic load factors of the bridge girder under different train speeds

C. The Wheel Load Reduction Rate

In the course of train operation, the wheel load reduction rate is a safety index for evaluating the derailment of a train by reason of the severe reduction of the load on one side of the wheel under the condition that the lateral force of the wheel approaches zero. The wheel load reduction rate is defined as the ratio of an axle load reduction of the wheelset in the load reducing side to the average static axle load, i.e., $\Delta P/\overline{P}$.

The average static axle load is calculated by

$$\overline{P} = \left(P_{st1} + P_{st2}\right)/2 \qquad (10)$$

The axle load reduction of the wheelset in the load reducing side is calculated by

$$\Delta P = \overline{P} - P_i \qquad (11)$$

where Pst1 and Pst2 are the static loads of the left and right part of the wheelset. Pi is the vertical force of the wheelset in the load reducing side.

The Chinese national standard [11] specifies that the safety standard for the wheel load reduction rate of a train is

$$\begin{cases} \Delta P/\overline{P} \le 0.65 & \text{danger limit} \\ \Delta P/\overline{P} \le 0.60 & \text{allowable limit} \end{cases} \qquad (12)$$

Fig. 9 gives the wheel load reduction rates under different train speeds between the TBP and TBPPS models. The results illustrate that the wheel load reduction rates between TBP and TBPPS are basically unchanged when the train speed is lower than 450 km/h. However, when the train speed is much larger, the wheel load reduction rate using TBP is still small, ranging around 0.25.

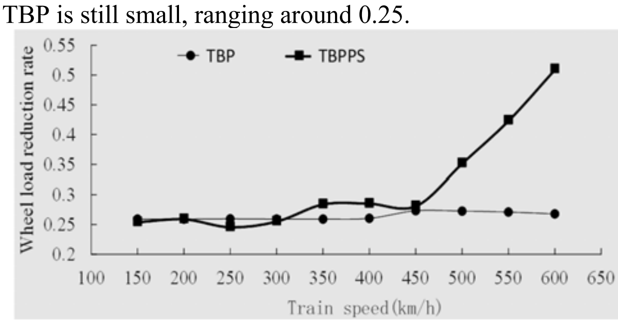


Fig. 9. The wheel load reduction rates under different train speeds

However, the wheel load reduction rate using TBPPS has marked variations, and increases to 0.51 that is close to the allowable limit when reaching resonance speed. Therefore, the pile-soil interaction effect should be considered as it deeply affects the safety evaluation of the train.

D. Train Vibration Acceleration

Train vibration acceleration represents the vibration amplitude of the train body, which objectively embodies the smoothness of the train operation. In view of the evaluation standard of the train vibration acceleration, the relevant specification from Eurocode is shown in Table V.

TABLE V. EVALUATION CRITERIA FOR TRAIN VIBRATION ACCELERATION FROM EUROCODE

Rating grade	Excellent	Good	Qualified
Train vibration acceleration (cm/s2)	100	130	200

Moreover, “Temporary provisions for the design of new passenger and cargo railways with a speed of 200 km/h”

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[12]and "Code for the design of the high speed railway" [13]offer the following standards in Table VI concerning the evaluation of train vibration acceleration.

TABLE VI. EVALUATION CRITERIA FOR TRAIN VIBRATION ACCELERATION FROM THE CHINESE CODES

Rating grade	Excellent	Good	Qualified
Train vibration acceleration (cm/s2)	245	295	363

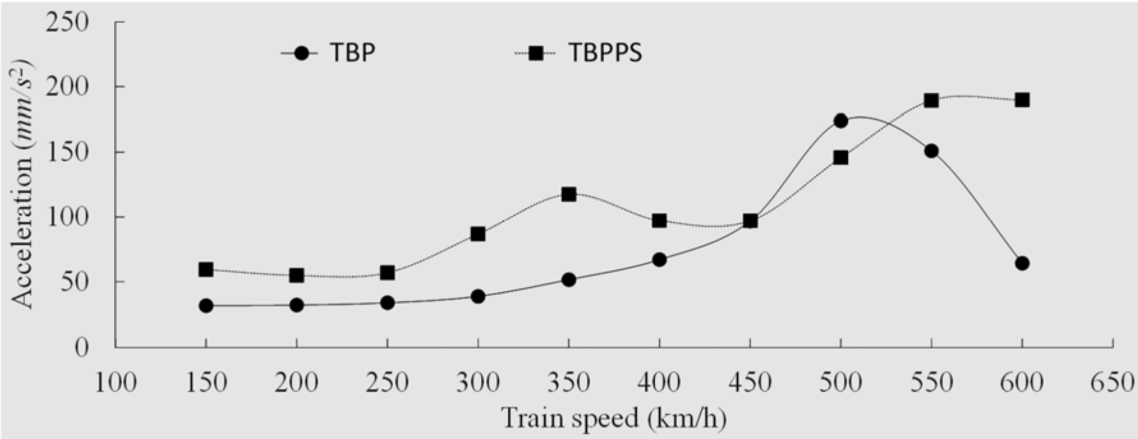

Fig. 10. Train vibration acceleration under different train speeds

Fig. 10 gives the train vibration acceleration under different train speeds between the TBP and TBPPS model. The results indicate that there are two different trends about the relationship between the train acceleration and the speed when pile-soil interaction is considered or not considered. For the TBP model, the train vibration acceleration increases first with the increase of train speed when it is below 450 km/h, then increases to the peak value when reaching the resonance speed, and finally decreases fast. As for the TBPPS model, the train vertical acceleration is, however, in a wave form with the increase of the train speed. When reaching the resonance speed, the vertical acceleration is the maximum. When the train speed is larger than the resonance speed, there is no apparent downward trend of the vertical acceleration. These results again show that the pile-soil interaction is extremely important for the train-bridge system when evaluating the smoothness of the train running.

V. CONCLUSION

The paper investigates the dynamic features of the train-bridge system with pile-soil interaction considered and not considered. The study is on the strength of a practical high-speed railway project in Hainan Province. A 32 m span simply-supported box girder bridge with a four-shaft locomotive using two-system suspension models is studied. The soil features based on the site survey are used to construct the pile-soil interaction model. Main findings are as follows:

(1) The natural frequencies and vibration modes with soil-pile interaction considered and not considered are largely different. The pile foundation and the soil reduce the corresponding frequencies of each mode order. The vertical vibration frequency of the bridge girder is increased from 4.87 Hz to 5.46 Hz when the pile-soil interaction is taken into account.

(2) The vertical displacement and acceleration of the bridge with soil-pile interaction considered and not considered vary with the increase of train speed by the similar means. When the train speed is close to 500 km/h, the bridge response is the most evident, indicating that it is the resonance speed in accordance with the theoretical value.

(3) There is no specific rule for the variation of the dynamic load factor with the speed. The dynamic load factor reaches the peak value when reaching the resonant speed. Therefore, a train speed limit should be designed for the train-bridge system to ensure safe operation.

(4) The results of the wheel load reduction rate and the train vibration acceleration are quite diverse with soil-pile interaction considered and not considered, especially at the resonance speed. These results show that the pile-soil interaction is rather crucial for the train-bridge system when evaluating the safety and smoothness of the train running. If the pile-soil interaction is not considered, the derivation will be considerably large.

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