Safety and stability of high-speed train moving on multi-span simply supported girder bridges in ground subsidence area

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Abstract. The dynamic interactions of a high-speed train, the track, and a simply-supported girder bridge are studied by theoretical analysis in this paper. A dynamic interaction model of the train-track-bridge system is established in ANSYS. Uneven pier settlement caused by ground subsidence and measured track irregularities are taken as the system excitation. The dynamic responses of the high-speed train are used as the safety and stability evaluation indexes when it passes over the bridge. A case study considering an eight-car high-speed train running on a four-span simply supported bridge in a ground subsidence area is analyzed. Relationships among different settlement periods, different train operation modes, and running dynamic performance under various speeds are obtained. The results indicate that speed is the dominant factor affecting the safety and stability of the high-speed train where local ground subsidence is present. In addition, when the speed of the train is high and ground subsidence is greater, the degree of settlement and the operation of the high-speed train are also important factors that affect the safety and stability.

1. Introduction
High-speed railways have developed rapidly in the world including China, Japan, Germany, etc. The high-speed railway mileage in China will reach 30,000 kilometers, covering more than 80% of the country. For a high-speed railway line, bridges may constitute more than 80% of its total length, e.g., the Beijing-Shanghai line in China [1]. Simply-supported girder bridges and continuous girder bridges are the most widely used.

Ground subsidence areas caused by groundwater overproduction may in turn cause ground collapse and ground structure damage, which already seriously affect homeland safety. The most extensive ground subsidence area in eastern China is also the densest area of the high-speed railway network. For example, Ji’nan and Dezhou are groundwater overproduction zones that threaten the safety of high-speed railway operations [2]. Hence, it is necessary to study the safety and stability of high-speed train-track-bridge systems, especially the ground subsidence area.

Research on vehicle-track-bridge dynamic interactions has increased in recent decades, and has focused on the following problems: (1) The dynamic response of trains running through dangerous areas such as bridge-embankment transitions, curved railway bridges, culvert transition zones, and so on [3]. (2) The dynamic performance of trains running through bridges under external adverse influences such as earthquakes, wind, bridge skewness [4]. However, little research related to ground subsidence areas and corresponding ground subsidence rules of vehicle-track-bridge systems regarding
safety and stability of high-speed trains have been conducted.

2. Dynamic Model of Train-Track-Bridge Interaction System in Ground Subsidence Area

The dynamic model for the vehicle-track-bridge interaction system is composed of a train subsystem, a track subsystem, and a bridge subsystem. Ground subsidence and track irregularity were regarded as external systems imported into the train-track-bridge system. Among them, the physical model of the high rail train is established on the basis of multi-rigid-body dynamics. Each carriage includes 1 body, 2 bogies and 4 wheelsets, respectively. The vehicle body and bogie consider the degree of freedom of sinking and floating, and the wheel pair considers the degree of freedom of sinking and floating, and the rest degrees of freedom are restrained. The dynamic interaction between cars is not considered.

The steel rail adopts the long track embedded ballastless track, whose vibration is mainly reflected by the rail vibration. The relationship model between the lower support of the track and the bridge is simulated by linear spring and damping element.

According to years of field observation and calculation, Li et al. concluded that the average annual settlement slope of DK330–DK340 in the Dezhou section of the Beijing-Shanghai high-speed railway is 0.0015% [2]. On the basis of Li’s research, the settlement of each pier of a four-span bridge 32 m in length can be calculated. Figure 1 shows the four-span simple support beam bridge model established in ANSYS. Table 1 shows the period settlement of each bridge pier. We studied the effect of ground subsidence on the performance of high-speed trains in the settlement period between 0 to 20 years in 5–year increments.

| Settlement period (years) | Slope of Pier 1(mm) | Settlemnt of Pier 2(mm) | Settlemnt of Pier 3(mm) | Settlemnt of Pier 4(mm) | Settlemnt of Pier 5(mm) |
|--------------------------|----------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 5                        | 0.0090%              | 2.88                     | 5.76                     | 8.64                     | 5.76                     | 2.88                     |
| 10                       | 0.0165%              | 5.28                     | 10.56                    | 15.84                    | 10.56                    | 5.28                     |
| 15                       | 0.0240%              | 7.68                     | 15.36                    | 23.04                    | 15.36                    | 7.68                     |
| 20                       | 0.0315%              | 10.08                    | 20.16                    | 30.24                    | 20.16                    | 10.08                    |

3. Finite Element Model

The bridge model is based on the Beijing-Shanghai high-speed railway in China. Train to eight cars is the marshalling, and we consider two types of train operation modes: a single line running from Beijing to Shanghai, the second is a double line running, considering both Beijing to Shanghai and Shanghai to Beijing simultaneously. The four-span high-speed rail bridge is simply-supported, and each simply-supported beam has a length of 32 m. The concrete strength grade is C50 in the China design code. The bridge is a box section, and the section size is shown in Figure 1. Boundary conditions of the bridge are: relative rotations around the vertical and transverse axes between the girders and supports are released in the model, and relative rotations around the longitudinal axis are restricted. The calculation parameters of high-speed train and rail are shown in table 2.
In this study, time histories are adopted for elevation irregularities as proposed by the FRA based on abundant measurements in railways within the USA. The following samples of track irregularity based on the bridge time histories can be generated by inverse Fourier transform 0 to simulate the vertical profile of the track are shown in Figure 2.
Figure 2. Track irregularity time histories sample

The type of track employed here is CHN 60, with a mass per unit length of 60.8 kg. The spacing of the rail fasteners is 0.65 m and the track mesh size is consistent with the spacing of the orbital fasteners. In this study, the car body and two bogies have three DOF in the Zc, Yc, and βc directions. The wheel sets have one DOF in the Zc direction. The DOF of the other directions of the rigid body are restricted. Train to eight cars is the marshalling, and we consider two types of train operation modes. We use the Conta175 element and the Targe169 element to simulate the contact surface and the target surface, respectively. The relationship between wheel and track is specified using the point and surface contact method, and parameters are set to evaluate the separation between a wheel and the track.

4. Discussion

4.1 Safety of High-Speed Train Running on Bridge in Ground Subsidence Area

In this section, we analyze the effects of high-speed trains running at 200 km/h and 400 km/h on the uneven ground settlement of the bridge for the two types of train operation mode. Figure 3 depicts the maximum offload factors obtained for the various speeds, various bridge pier’s annual settlements, and different train operation modes considered. The maximum offload factor increases with increasing train speed overall, and the maximum value of 0.561 occurs at 400 km/h for double line running without pier settlement. The operation mode of the train has little effect on the load reduction rate when the train is running at low speeds and the effect increases as the speed increases. The load reduction rates of the single and double line are 0.551 and 0.560, respectively at 400 km/h and the delta is 0.009, when the local surface is not subsiding. The load reduction rates of the single and double line are 0.706 and 0.764, respectively at 400 km/h and the delta is 0.058, when the settlement period is 20 years. Note that for the same settlement period, the same operation mode, and different operation speeds, the load reduction rate increases with increasing speed of the train (increases by 0.04-0.05), but at speeds higher than 250 km/h, the increment is approximately 0.1. For the same speed, operation mode, and settlement for different periods, as the settlement period increases, the wheel load lightening rate increases by 0.02-0.03, but at 400 km/h, owing to ground subsidence and wheel load reduction, significant changes in load lightening rate occur, with an increase of approximately 0.07. Note that when the train reaches a speed of 400 km/h, once the ground is completely settled, the weight reduction will exceed the maximum allowable limit of 0.6
Speed is the most important factor with respect to running safety. Particularly, when the train runs at a speed of 400 km/h, ground subsidence will seriously affect the safety of the train. In conclusion, to ensure the safety of train operation, the train speed must be strictly limited.

### 4.2 Maximum Acceleration of Car-body

Figure 4 shows the maximum acceleration changes with different modes and train speeds versus ground settlement. Note that when the train speed is less than 300 km/h and the settlement period is less than 10 years, the train operation mode has little influence on the maximum acceleration of the train. When the settlement period is greater than 10 years and the train speed exceeds 300 km/h, subsidence will have a significant impact on the maximum acceleration of the vehicle body. For example, when the speed of the train is 300 km/h and the settlement period is 0, the maximum acceleration of the single line and double line are 0.057 g and 0.058 g, respectively, and the delta is 0.001 g. But when the settlement period is 20 years, the maximum acceleration of the train running in the single line and double line at 300 km/h is 0.076 g and 0.081 g, respectively, and the delta is 0.005 g. The maximum acceleration of the body increases with increasing speed and settlement period. We can observe in Figure 4 that the maximum acceleration of the train running during settlement period 0 at 300 km/h is 0.057 g and the value increases to 0.063 g when the speed is 400 km/h. The maximum value is 0.097 g and is less than the allowable value of 0.13 g when running at 400 km/h when the settlement period is 20 years.

In brief, it is important to control train speed and perform ground subsidence monitoring to ensure the stability of trains running over 300 km/h and a settlement period greater than 10 years.

### 4.3 Sperling Ride Index

Figure 5 shows the values of Sperling index corresponding to the various settlement periods. It can be observed that the train speed has a significant influence on the Sperling riding index. As the speed increases, the Sperling index will also increase, which indicates a reduction in passenger comfort. Also note that pier settlement and operation mode have a slight effect on riding comfort for the same speed. At the same speed and settlement period, the Sperling index of the double line is greater than the single line. For design speeds of 300 km/h, the maximum Sperling index obtained is 2.58 when the settlement period is 0 years, and the maximum Sperling index steadily increases to 2.96 as the speed increases to 400 km/h. However, these values are 2.71 and 2.61, respectively for 20 years of settlement and double line running. When the train reaches a speed of 400 km/h, once the ground is completely settled, the ride quality will be better than the qualified level of 3.0 or less.

In summary, it can be concluded that the influence of speed far outweighs those of the annual settlement and operation mode in terms of the Sperling index.

### 5. Conclusions

This study proposed a 3-D dynamic nonlinear interaction model for a high-speed train-track-bridge
system which is based on a single platform. The model considered the effects of rail irregularities, annual settlement, wheel/rail contact, operation mode, and coupling. The model is based on the real case of the Beijing-Shanghai high-speed railway and was shown to be effective for evaluating the safety and stability of high-speed trains running on simply-supported bridges. From the analyses, it can be concluded that: (1) Settlement period, running speed, and operation mode of the train play a vital part with regard to the safety and stability of the high-speed train. (2) Running speed is the dominant factor contributing to the safety and stability of the high-speed train. (3) The Beijing-Shanghai high-speed railway has a large safety reserve; however, when the settlement period is over 10 years and the train speed exceeds 300 km/h, the degree of settlement and the operation mode will also have a significant impact on the safety and stability of the train. (4) The research results of this paper can guide development of safety limits in ground subsidence areas, and provide an early warning analysis method.

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