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Modelling stress distribution in substructure of French conventional railway tracks

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HIGHLIGHTS

- Comparison between track-bed stress measurements with existing elastic diffusion models.
- A new modified spread model based on stochastic stress diffusion is presented.
- Stress dynamic amplification is taken into account in the new proposed model.
- The modulus ratio of adjacent layers governs the stress diffusion in depth.

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ABSTRACT

Many studies were conducted on the modelling of stress distribution of soil foundations based on the elastic theory or uniformly spread hypothesis, but few works focused on the modelling of dynamic stress distribution in railway substructures. In this study, field monitoring was performed at Vierzon, France, using two embedded stress sensors. Dynamic stress data were recorded during train passages at different speeds, from 60 km/h to 200 km/h. Note that the Vierzon site involves a conventional line that is characterised by the presence of an interlayer soil, sandwiched between the ballast layer and the subgrade. The recorded data was firstly used to verify the existing models currently used in practice, revealing the advantages and drawbacks of such models. Then, based on the theory of stochastic stress diffusion in particulate media, a modified load spread model was developed. Comparison with the recorded data shows the relevance of the proposed model. In particular, significant effect of modulus ratio bewteen two adjacent layers on stress distribution was evidenced.

1. Introduction

Nowadays, there is a significant growth in passenger and freight traffic on railways across the world. In France, the railway network is composed of conventional lines (94%) and high-speed lines (6%). Normally, problems related to superstructure (rails, fastening system and sleepers) can be visualised and solved rapidly [45]. However, problems occurred in the substructure (ballast and subgrade) are relatively difficult to be identified and often expensive to remediate [17]. To analyse the problems related to the substructure, it is of paramount importance to correctly evaluate the stress distribution in it. This is particularly important in the context of increasing the train speed and axle weight for improving the traffic service.

The train-induced stress in substructures is dynamic by nature when the train speed exceeds a certain value [36,49,9]. In practice, the dynamic stresses were usually expressed as function of static load and an impact factor [10,4,18,39,14,2,52,42]. The impact factor of vertical wheel load is frequently determined at the rail level: the static vertical force and dynamic force are measured by strain gauges attached to the rail, and the values are used to determine the impact factor. Then, empirical equations or Boussinesq solutions are usually applied to assess soil stress in depth [45,40]. Obviously, other more realistic methods need to be developed based on the direct measurement of dynamic stress in substructures.

Many previous works focused on field experimental investigation of soil stress distribution in railway tracks. Before 1980s, the stress distribution was determined by pressure cell measurements under static loading and quasi-static conditions (<100 km/h) [47,48,43,23]. After 1980s, with the development of high-speed railway lines, the measurement of dynamic stress becomes more

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and more important. Kempfert and Hu [30] measured the dynamic stress in the substructure of silty sand at two depths for concrete slab tracks in Germany, with train speed up to 400 km/h, and they determined the impact factor based on the measurement. Fan [19], Yang and Liu [54], and Bian et al. [9] also performed field measurements of dynamic stress within 4 m depth for ballastless tracks in China (>300 km/h). The recorded data allowed them to propose the ranges of impact factor for different sites or different soils. For the conventional lines, Cui et al. [12] performed field monitoring at the Moulin Blanc site with measurements of acceleration at two different depths, but no direct dynamic stress measurement was conducted. There is thus necessity of performing such measurement in conventional track substructures.

As far as the modelling of rail-track behaviour is concerned, 2.5D and 3D models using finite element method were developed by several authors [25,22,53,56,13]. These models can successfully describe the vibration in substructures, but suffer from complexity and time consuming calculation. On the other hand, simple approaches, such as empirical equations or Boussinesq solutions, are usually used in practice [23,14,45,40]. But most of them take the substructure as a homogeneous media. This is far from the real situations of track substructures. For example, in the French conventional lines, there is an interlayer (ITL) between the ballast layer and subgrade (SBG), created by interpenetration of fine particles from SBG and ballast grains under the traffic effect [11,12,15,16,50,51,33]. The presence of this ITL brings up the complexity in modelling the stress distribution in substructures.

In this study, the train-induced stress in the substructure of a French conventional line was monitored at two different depths (in ITL and in SBG) and at different train speeds, from 60 km/h to 200 km/h. Based on the recorded data, the speed impact factor was analysed, and the Boussinesq elastic models and load spread model were evaluated. Then, based on the theory of stochastic stress diffusion in particulate media [6], a modified load spread model using cumulative Gaussian stress distribution was developed. The influences of internal friction angles and the elastic modulus of soils of different layers were also evaluated.

2. Site description and field monitoring

Field monitoring was performed at Vierzon in France, in the conventional line 'Orleans – Montauban'. This site was selected due to the good state of the different track elements, its geographical situation and traffic conditions. An intercity train was employed for the experimentation, consisting of one locomotive BB22000 and seven 'Corail' coaches. The configuration of the test train is shown in Fig. 1. The wheel loads (half-axle load) are 112.5 kN and 52.5 kN for the locomotive and the Corail coaches, respectively. Six train speeds were considered: 60 km/h, 100 km/h, 140 km/h, 160 km/h, 180 km/h and 200 km/h.

By geophysical and geotechnical prospecting on the experimental site, a geological profile was defined with four different layers as shown in Fig. 2: Ballast, Interlayer (ITL), Transition layer (TL) and Subgrade (SBG). The thickness of the ballast layer is 50 cm in average with 41 cm fresh ballast and 9 cm fouled ballast. The average thickness ITL with high density and low permeability of coarse-grained soil is 40 cm. The TL was found below ITL, containing more fines and less coarse grains ($D_{\max}$ = 20 mm). The SBG consists of a sandy silt (D_{50} = 0.3 mm, I_P = 18). The elastic modulus estimated using empirical formulations from the tip resistance obtained from light dynamic penetrometer tests (PANDA) are 133 MPa, 103 MPa, 95 MPa, 77.5 MPa for Ballast, ITL, TL and SBG, respectively [34].

The disposition of sensors is specified in Fig. 2, and the technical specifications of the sensors are presented in Table 1. Fontainebleau sand was used to fill the borehole, 5 cm over the sensors to ensure a good contact between the sensors and the soil nearby. Then, the borehole was back-filled and compacted with an artificial ITL soil [33]. After instrumentation, the test train ran over the experimental site at the six defined speeds and the response of each sensor was recorded.

3. Results and discussions

3.1. Results

After multiplying time by train speed, the time-domain signals (Fig. 3(a) and (b)) were converted to distance-domain signals (Fig. 3(c) and (d)) and the typical longitudinal vertical stress signals for ITL and SBG at 60 km/h, and 200 km/h are presented. Note that the initial point (distance = 0 m) in X-axis corresponds to the start of recoding time (about 80 m from the arriving train position). The signals are of 'M' shape, each 'M' representing a bogie load. The two peaks in a 'M' signal represent two axles in a bogie. It can be observed that the distances of the two peaks are keeping constant when the train speed increases from 60 km/h to 200 km/h. This justifies the repeatability of the measurements with different train passages. In addition, the parts between two 'M'-shaped signals correspond to those of coaches delimited by bogies. For these parts, negative stress values were recorded. This is to be attributed to the reaction of uplift force or rest sleeper [45,35], and these values are taken into consideration in calculating the stress amplitude by considering the whole amplitude from the lowest value to the highest one.

For clearly observing the difference of stress, the last 'M' shaped signals in Fig. 3 are extracted and zoomed in Fig. 4. The maximum stress developed under coaches' bogies in ITL is about 8 kPa (Fig. 4

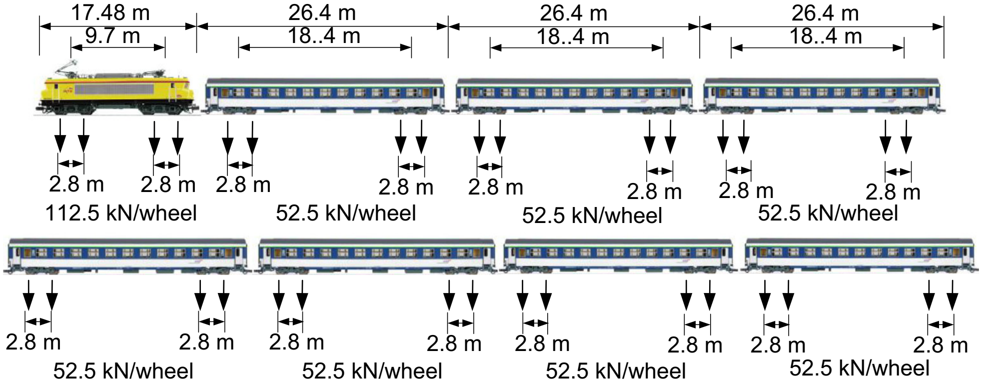

Fig. 1. Configuration of the Intercity train employed and the corresponding static wheel loads.