Critical Velocity of High-Speed Train Running on Soft Soil and Induced Dynamic Soil Response

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Abstract

The determining of the critical speed under train operation remains difficult due to the complex properties of the track, embankment and ground. In this paper, a dynamic analysis model comprising track, embankment and layered ground was proposed based on the two-and-half-dimensional (2.5D) finite elements combining with thin-layer elements to predict vibrations generated by train moving loads. The track structure is modeled as an Euler-Bernoulli beam resting on embankment. The train is treated as a series of moving axle loads; the embankment and ground are modeled by the 2.5D finite elements. The dynamic responses of the track structure and the ground under moving axle loads at various speeds are presented. The results show that the dynamic response of ground induced by moving constant loads is mostly dominated by train speed and the stiffness of the topsoil. The critical speed of a train moving on an embankment is higher than the Rayleigh wave velocity of the underlying soil, and softer soils results in lower overall critical speed of the system.

Keywords: 2.5D finite element method; High-speed train; Critical speed; Track-embankment-ground
1 Introduction

As train speed increases, dynamic responses of railway track and ground along the railway line become more substantial. For a high-speed train running on soft soil, resonance may occur and consequently the dynamic responses of the track and ground are dramatically amplified. The speed at which extraordinarily large dynamic response occurs is named as the ‘critical speed’ (Costa, Calçada et al. 2010). At the critical speed, train moving loads induce strong vibration in track structure, and increase the risk of train derailing and track structure damage. In 1998, an extensive measurement was undertaken by the Swedish State Railways on soft soil ground in Ledsgard (Kaynia, Madshus et al. 2000). Which indicated that the vehicle and track generated significant vibrational resonance as the speed of the train was increased to 200 km/h. The maximum amplitude of track vibration reached 15mm–20 mm, which exceeds the safety limits of train operation.

Vibrations induced by traffic loads have been extensively studied, series of results have been achieved (Krylov 1995; Metrikine and Dieterman 1997; Jones, Sheng et al. 2000; Bian 2006; Zhou and Jiang 2006; Bian and Hu 2007; Bian, Cheng et al. 2014). Takemiya (Takemiya and Bian 2005) investigated the dynamic interactions between a track system comprising continuous rails and discrete sleepers, and the underlying viscoelastic layered half space ground, and compared differences in the results between the layered ground model and the Kelvin ground model. Galvin et al. (Galvin P 2010) proposed a general and fully three-dimensional multi-body-finite element-boundary element model to analyze the dynamic behavior of a transition zone between ballast track and slab track. Bian et al. (Bian X 2007) presented a finite element combined with a thin-layer element method to study dynamic track-ground dynamic interaction under train moving loads.

The majority of the aforementioned works used simplified beam-on-ground models to analyze the ground vibrations under train moving loads. Although these solutions could be used to understand the vibration generation mechanism under train moving loads, these methods are not able to deal with the complex track structures and ground soils. Determining the critical speed of train operation remains difficult due to the complex properties of the track, embankment and ground. Three-dimensional finite element models may be used to account for details of the track structure and ground. But its main disadvantage is very time-consuming (Bian X 2007; Zhai WM 2009; Galvin P 2010). To overcome the disadvantages of traditional numerical methods for simulating train induced soil vibrations, Yang and Hung (Yang YB 2001) originally proposed a high-efficient 2.5D finite element method for treating vibrations in half space induced by moving trains, and the infinity of the ground was dealt with by an infinite element in wavenumber domain. And later, they used the same method to investigate...
underground train induced ground vibrations (Yang YB 2008; Hsiao-Hui H 2010). Recently, Bian et al. (Bian, Cheng et al. 2014) used a 2.5D finite combined with thin-layer element to study ground vibrations induced by trains moving at various speeds.

In this paper, an elaborated 2.5D track-embankment-ground finite element model is established to study the dynamic response of track structure under a series of train wheel axle loads. Firstly, critical speed of this model under train operation has been determined. A parametric study is performed based on this model to study the influence of soil stiffness on the critical speed under train operation. Finally, some conclusions are presented.

2 Track-embankment-ground Interaction Model

In this paper we use a 2.5D finite element model combined with thin-layer element to study the dynamic response of the three-dimensional ground under train moving loads. First, the wavenumber transform with respect to the track direction is applied on the equations governing wave propagation. Therefore, the vibration along the track direction is expressed by discrete wavenumber. The embankment and ground in the transversal-vertical section are discretized and modeled by 4-node quadrilateral elements with specific discrete wavenumbers. Each node of the element has three degrees of freedom allowing wave propagation in three-dimensional space to be taken into account faithfully. Details about the derivation process can be found in (Bian, Cheng et al. 2014). A simplified illustration of the computation model is shown in Fig. 1. The train is modeled by a series of vertical point loads at track surface along the rail which move along the track at constant speed. Four observation points are indicated in Figure 1 at point A (the track center), point B (the bottom of the embankment), points C and D (ground surface). The distances of these points to the track centerline are 0, 4 m, 14 m and 24 m, respectively.

![Track-embankment-ground interaction model](image)

**Figure 1:** Track-embankment-ground interaction model (not to scale)

The ground is treated as a layer soft soil resting on a layer of stiff soil. The parameters of
embankment and ground are shown in Table 1.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (m)</th>
<th>Density (kg/m³)</th>
<th>S-wave speed (m/s)</th>
<th>Rayleigh-wave speed (m/s)</th>
<th>Loss factor</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embankment</td>
<td>1.0</td>
<td>2,100</td>
<td>200.0</td>
<td>188</td>
<td>0.05</td>
<td>0.40</td>
</tr>
<tr>
<td>Soft soil</td>
<td>6.0</td>
<td>1,800</td>
<td>85.0</td>
<td>80</td>
<td>0.05</td>
<td>0.35</td>
</tr>
<tr>
<td>Stiff soil</td>
<td>17.0</td>
<td>2,000</td>
<td>150.0</td>
<td>142</td>
<td>0.05</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Table 1: Parameters of the embankment and ground

Figure 2 shows the geometry of the wheel axle weight distribution of the high-speed train used in this study. \( P \) and \( L \) represent the axle load and the train length; \( a \) and \( b \) are the distance between adjacent axles. The train used in this paper is China high-speed train CRH3. It includes 8 coaches, the length of a coach, \( L \) is 25 m, \( b \) is 15 m, \( a \) is 2.5 m and the axle load \( P \) is \( 1.4 \times 10^5 \) N. The mass of the two rails is 120 kg/m. The bending stiffness of rail is \( 1.26 \times 10^7 \) N·m, and its loss factor is 0.01.

![Figure 2](image.png)

Figure 2: Geometry of wheel axle load distribution of a train

3 Numerical Results and Discussion

3.1 Determine the Critical Speed of This Model under Train Operation

In this section, the train load is simplified as a series of constant loads. Three typical speeds are adopted in the numerical computation, super-critical speed (200 m/s), estimated critical speed (120 m/s) and sub-critical speed (50 m/s). The time-history and root mean square (RMS) displacement responses of the four observation points are shown in Figure 3. The ground vibrations from a train load moving at a speed of 50 m/s can be regarded as similar to the pseudo-static deformation induced by the total weight of the whole train geometry; and no significant wave propagation phenomena at ground surface is observed. The displacement at points C and D is close to zero. The propagation of vibration phenomenon at all four observation points becomes more obvious for a train running at estimated critical speed (120 m/s) and super-critical speed (200 m/s). At the track surface structure (points A and B), vibrations induced at a speed of 120 m/s are much larger than those induced at either sub or super-critical speed, which indicates that ground response does not always increase with speed. Away from the track, the responses at points C and D have large amplitudes, which decrease slowly when train runs at critical and super-critical speeds.
Figure 4 presents the relationship between vertical displacement amplitude and train speed. It shows that the amplitude of displacement response increases slowly with speed at relatively low speed. The response increases sharply once the train moves at speed over the Rayleigh wave velocity of the upper soil layer below the embankment (80 m/s). The amplitude maintains a higher value when the speed of train is higher than the Rayleigh wave velocity of the subsoil. Based on reference (Alves Costa P), the critical speed of the track-ground system is defined as the train speed which induces the maximum amplitude response of the track structure. Figure 4 shows that the critical speed for model is 120 m/s, which is higher than the Rayleigh wave velocity (80 m/s) of the topsoil. That is because of the existence of track and embankment structures.
Figure 3: Vertical displacement response at the speed 50 m/s, 120 m/s and 200 m/s at observation points (a) A, (b) B, (c) C and (d) D (left) distance-history of displacement, (right) RMS value of displacement

Figure 4: Vertical displacement response under varied speeds

3.2 Parametric Study

The critical speed (120 m/s) of the aforementioned model is higher than the Rayleigh wave velocity (80 m/s) of the topsoil. In this section, consider three typical topsoil: a soft soil (No.1 topsoil), a moderate soil (No.2 topsoil), a hard soil (No.3 topsoil), are list in Table 2. Then, the influence of topsoil's stiffness on critical speed can be revealed.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (m)</th>
<th>Density (kg/m³)</th>
<th>S-wave speed (m/s)</th>
<th>Rayleigh-wave speed (m/s)</th>
<th>Loss factor</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1 topsoil</td>
<td>6.0</td>
<td>1,800</td>
<td>83.35</td>
<td>78.35</td>
<td>0.05</td>
<td>0.35</td>
</tr>
<tr>
<td>No.2 topsoil</td>
<td>6.0</td>
<td>1,500</td>
<td>130.0</td>
<td>122</td>
<td>0.05</td>
<td>0.35</td>
</tr>
<tr>
<td>No.3 topsoil</td>
<td>6.0</td>
<td>1,550</td>
<td>152.0</td>
<td>143</td>
<td>0.05</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Table 2: Parameters of three typical topsoil

Vertical displacement response under three typical soil at the speed 50, 120, 150 and 200 m/s at observation point A (left) distance-history of displacement, (right) amplitude values of displacement under varies train speed are show in Figure 5. It can be find that the vertical displacement of soft soil
is greater than a hard one when they under the same train speed. The amplitude of vertical displacement also arise when the same train speed applied on a soft soil. Under the moving constant load, the critical speed of three typical soil are 120m/s, 150m/s, 160m/s, respectively.

Figure 5 shows that softer soils results in lower overall critical speed of the system. This conclusion suggests that reinforce of the soft soil foundation can also improve the critical speed of the system.

(a) No.1 topsoil (soft soil)

(b) No.2 topsoil (moderate soil)

(c) No.3 topsoil (hard soil)

Figure 5: Vertical displacement responses for conditions of speed 50 m/s, 120 m/s, 150 m/s and 200 m/s. (left)
distance-history of displacement, (right) amplitude of displacement (a) No.1 topsoil (soft soil), (b) No.2 topsoil (moderate soil), (c) No.3 topsoil (hard soil)

4 Conclusions

This paper applied a 2.5D finite element combined with thin-layer element model to analyze the vibrations induced by moving trains at sub-critical speed, critical speed and super-critical speed, accounting for three typical soil. From the computational results, the following conclusions can be made:

1. Track response does not always increase with the train speed. There exists a speed range (with inclusion of the critical speed) in which the train induces peak vibration intensity in the track. For train speeds outside of this range, the track vibration remains small.

2. There exists a critical speed in the track-embankment-ground system for the operation of a high-speed train. As the embankment and track structure have greater stiffness than that of the underlying ground soils, the critical speed is higher than the Rayleigh wave velocity of the upper layer soil.

3. No matter in soft soil or hard soil, the critical speeds are always larger than the Rayleigh wave velocity.

4. A softer soils results in lower overall critical speed of the system, which means reinforce of the soft soil foundation can also improve the critical speed of the track-embankment-ground.

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References


