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High speed railway track dynamic behavior near critical speed

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ABSTRACT

This study was performed on the Amtrak Northeast Corridor (NEC) at Kingston, Rhode Island where is known as the Great Swamp and requires more frequent track maintenance. It was suspected that the so-called "critical speed" condition might exist at this particular location. The critical speed is the speed at which trains travel on the soft subgrade close to or higher than the Rayleigh wave velocity of the subgrade soil. The conventional understanding of the "critical speed" would expect both a cone-shaped ground wave motion and substantial amount of track deflections. Field investigations combined with a validated 3-D dynamic track-subgrade interaction model were used to evaluate the track performance and determine if the critical speed effect exists at the Kingston site. The track performance was investigated by a three-by-three (3 × 3) array of accelerometers. Site investigations were carried out to characterize the site and provide input data for modeling. According to the field measurements and model results, the rail did not show excessive deflections; however, ground surface wave propagation had been detected with a cone-shaped mode. In other words, the cone-shaped ground wave motion and the increase in rail deflection did not occur at the same time as the conventional understanding. In addition, the model results pointed out that the stress level in the subgrade would encounter a significant increase under the current operational speeds (less than 250 km/h) rather than excessive rail deflections and the rail deflections will increase dramatically at the simulated train speeds of over 300 km/h. Therefore, the "critical speed" is defined in two levels for the Kingston site: 1) The speed causing significant stress increase in the ballast and subgrade, at which more frequent ballast maintenance is needed; 2) The speed causing significant increase in rail deflection, at which derailment becomes a concern.

1. Introduction

Increasing speed brings new challenges to conventional railway engineering, which include rail system control, passenger safety and comfort, and noise and vibration hazards. Ground-borne vibration induced by high speed rail is the focus of this paper. According to previous research [1–10], high speed trains on soft ground can induce a significant increase in vibration level when trains move at the critical speed. Theoretical modeling of a rail as a beam supported by track structure and ground reveals that the dynamic amplification will occur when train reaches a certain speed, this has been studied since 1927 [1]. For typical soil properties, this previous modeling suggests dynamic amplification around 1800 km/h, which is greatly above the realistic HSR speed, because only pressure wave velocity is considered in Timoshenko's theory. Hence, for a long period, the train loads have been assumed to be quasi-static moving loads. However, Krylov [2] considered that a train will encounter something equivalent to the 'sound barrier' when reaching the velocity of Rayleigh surface waves propagating in the ground. This phenomenon is somewhat analogous to the sonic boom of supersonic jets. The velocity of Rayleigh waves traveling in soft sandy soils is 320–470 km/h (89–131 m/s) [2], which is already reachable by today's high speed trains outside of The United States. Furthermore, for peat, marine clays, and other soft clays, the Rayleigh wave velocities could be as low as 110–140 km/h (30–40 m/s) [3].

The critical speed is the velocity of the moving train that leads to higher amplification of the dynamic response of the track structure and subgrade. For a conventional railway track, the critical speed is close to the Rayleigh wave velocity of the subgrade soil. Rayleigh waves typically have a speed slightly less than shear waves. Thus, soil with low shear-wave velocity needs much attention because it is susceptible to increased vibrations when the Rayleigh Wave speeds are approached. As a consequence, the high-level of track deflections impose limits on train speed. Another phenomenon of the critical speed effect is the

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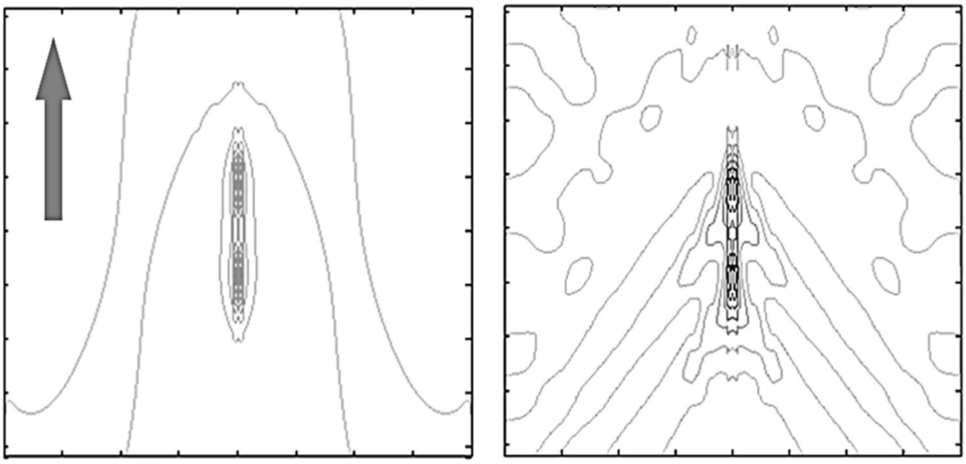

Fig. 1. Vertical displacement fields of the ground surface when train running at different speeds: low speed (left) and critical speed (right) [14].

cone-shaped wave motion of ground surface which is analogous to a boat moving through water. As can be seen in Fig. 1, the displacement fields of the ground surface become a cone-shaped wave motion as the train speed reaches the “critical speed” and the magnitude of the displacement increases at the same time. For an example, X-2000 (Swedish HSR), in 1997, was running at the maximum speed on the Goteborg-Malmo line and generated excessive vibration in the soil and overhead contact line support poles [11]. Furthermore, at Ledsgard Sweden, a new railway line with design speed of 200 km/h encountered large deflections of track on soft cohesive soil. The speed of trains had been decreased from 200 km/h to 160 km/h, then to 130 km/h [12]. The reason for the large deflections of track turned out to be the approaching of critical speed. Also, the similar phenomenon happened at Northern Ireland Railways where the subgrade is constructed on peaty soils [13].

In this study, a previously developed and validated 3-D dynamic track model [14–16] is used to predict the track and ground vibrations and substructure performance under trains moving at “Critical Speeds”. The dynamic track model is a complex system with train, track and soil subgrade. The vehicle model is a detailed system with car body, primary and secondary suspension system. The ballasts-soil interface is numerically modeled by the complex Green's function [17] to account for different speeds and subgrade modulus. The subgrade is modeled by 3D finite element method so that the motion of wave propagation can be completely simulated.

To investigate the so-called “critical speed”, the site was chosen to be a section of the Northeast Corridor located within the Great Swamp Management Area, Kingston, Rhode Island, where the track is underlain by a soft organic silt (peaty) deposit. This is most favorable for this research since the velocity of Rayleigh wave may be low enough to observe the critical speed effect resulting from both high speed trains and conventional passenger trains. A series of methods, such as Ground Penetrating Radar (GPR), Seismic Wave Velocity Testing (SWVT) and Dynamic Cone Penetrometer (DCP), were used to investigate the site. Also, a 3 × 3 array of piezoelectric accelerometers was used for the measurement of near and far field track and ground response.

2. Site investigation

The Northeast Corridor (NEC) is a rail line owned primarily by Amtrak, which runs 731 km from Boston, Massachusetts to Washington, D.C. This line has sections of Class 8 Track allowing speeds of 250 km/h. The section of the NEC that is of interest to the critical speed study is a straight section of track that runs northeast/southwest through the northern section of the Great Swamp, Rhode Island, just to the west of South Kingston, Rhode Island. Currently, this section of the NEC is a double track section that is used for both HSR trains and regional passenger trains.

The surficial geology in this region where the Great Swamp is located is comprised entirely of various glacial deposits (moraines, kames, outwash, etc.) and swamp deposits. The soil deposits are dominated by ground moraine, subglacial till, undifferentiated ice contact deposits, and an organic swamp soil deposit. The swamp deposits are completely underlain by this ground moraine. The thickness of the swamp deposits varies from 2 m to 7.5 m, with most of the deposits having the lower range of thickness. It would not be uncommon to find peaty soil with high water content to have Rayleigh wave velocities as low as 110 km/h (30 m/s). Two sites (Fig. 2.) were chosen to investigate if the critical speed effect exists in this area. Field and laboratory investigations were conducted to characterize the in-situ subgrade conditions.

2.1. Ground penetrating radar (GPR) and light detection and ranging (LiDAR)

Ground Penetrating Radar was collected at the sites by HyGround Engineering in June 2011. A hi-rail truck with antennas mounted on the left, center, and right sides was used to survey the track. The data were processed to estimate the fouling indices, layer depths, and moisture profiles. Geometry and LiDAR data are also shown with the GPR data. Light Detection and Ranging data were provided for the track and right of way which were used to develop accurate ground surface topography.

According to the investigation, Site 1 has a spot of slightly fouled ballast, roughness and moisture near the area where measurements were taken. Moisture is present at the top layer of soil on the right (towards Track 2). Site 2 has mildly fouled ballast all around the site and moisture down to the second layer of both the left and right side of Track 1. There is a spot of very mild roughness too. Both sites are in a fill, over several hundred feet on each longitudinal side which made these locations an excellent place to perform field measurements.

2.2. Seismic wave velocity testing (SWVT)

The SWVT method is an in-situ seismic method for determining shear wave velocity profiles. Testing is performed on the ground surface, allowing for less costly measurements than with traditional borehole methods. A dynamic impact is used to generate surface waves which are monitored by two or more receivers at known offsets. Fig. 3 shows an example of the SWVT test. It plots the wave traveling time versus surface displacement. Different curves represent the signals received at different locations. The strongest response (usually the first downward peak) is the time point when the surface wave arrives. The surface wave velocity is determined by the time lag and length of offset,