Field Measurement of Ground Response of Critical Speed High Speed Trains on Soft Soil

FIELD MEASUREMENT OF GROUND RESPONSE OF CRITICAL SPEED HIGH SPEED TRAINS ON SOFT SOIL

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ABSTRACT
Trains traveling over soft soil conditions at velocities approaching critical speed (the Rayleigh wave speed) will produce significant track vibrations that will adversely affect the track structure and adjacent structures. Softer soil conditions result in lower critical speed and a greater potential for high amplitude response. A field study has been initiated to investigate the dynamic response of soft soils that may be subjected to near critical speed from high speed train traffic. The section of track being investigated is located along the Amtrak Northeast Corridor in the Great Swamp Management Area near Kingston, Rhode Island, United States. This section of the Northeast Corridor is where the Amtrak Acela high speed train travels at velocities of 241 kph. The soil conditions consist of soft swamp deposits of clays, silty clays and peat. The instrumentation consists of an array of triaxial accelerometers strategically placed along the centerline of the track as well as at locations adjacent to track. Timing of the train arrival is determined using high speed video to precisely capture the arrival of the train to the accelerometer array. The Array is designed to be transportable to enable testing of several sections of rail in the Great Swamp Management Area and other related sites.

INTRODUCTION

Critical speed of a train occurs when a moving train causes substantial amounts of track vibrations (DeNie, 1948; Sunaga, et al., 1990; Rehfeld, 1994; Hillig, 1996; He, et al., 2009). When a train is traveling at or near critical speed excessive horizontal and vertical vibrations occur producing a bow wave, analogous to aircraft traveling at speeds approaching, matching or exceeding the speed of sound. Typically, this will occur between 200 km/hr to 300 km/hr. This phenomenon was first observed and recorded at a site in Ledsgard, Sweden, which required soil improvement as a countermeasure to solve the problem. In the United States, Amtrak has experienced more frequent ballast maintenance needs on a section of the Northeast Corridor (NEC) in the Great Swamp Management Area in Rhode Island (Huang and Chrismer, 2013).

Critical speed behavior is dependent upon the train suspension system, train speed, rail surface smoothness, track structure, track substructure and subballast ground conditions. In order to get a better understanding of these factors, computer models have been developed to simulate the behavior. The computer based analysis has been useful in predicting behavior. What is required to fully understand critical speed behavior is to have reliable instrumentation of a site that is susceptible to such behavior. Such an instrumentation plan has been developed to measure near surface ground motion near the NEC section in the Great Swamp. It is intended that the measurements will be useful in verifying the ground response models being used to evaluate sub critical and supercritical speed conditions.

MODELING SURFACE WAVE BEHAVIOR

Dynamic modeling of railroad vehicle, track structure and substructure have been studied over a long period of time (Knothe and Grassie, 1993). Most took the approach of modeling the dynamics using a two-dimensional model because of the need to minimize computational complexity. These methods included analytical and numerical models. (Cai and Raymond, 1994, Anderson and Oscarsson, 1999; Samavedam et al., 1997, Huang, et al., 2010). To model wave motion under HSR trains, it is necessary to use a three-dimensional model to properly characterize the wave propagation through the soil.

First three-dimensional studies simplified the analysis by modeling the soil as an infinite half space or as a layered system. Using this model, a closed form solution for a moving point load can be determined (Shen et al., 1999). By modeling the rail, sleeper and ballast as an upper structure and the soil as a substructure, the solution can be treated as harmonic motion with spatial and temporal dependency.

Later, Shen et al. (2004) coupled the track model with a car model to study vibrations resulting from rail surface roughness. A major advantage of this model is an efficient computational scheme. As this model requires a simplified geometry, more complex models require the use of three-dimensional finite element modeling. Although three-dimensional analysis can model spatial variations in ground conditions (e.g., changes in grade, adjacent embankments, tunnels, etc.), these computationally demanding modes often make this type of analysis impractical. Other approaches have been taken to reduce computations by making the track properties constant as the train travels along the track (Yang et al., 2003; Takemiya, 2003; Bian, 2004). Discrete methods and boundary element methods have been used to improve computational demand (Takemiya and Bian, 2005; O'Brien and Rizos, 2005).

Huang and Chrismer (2013) created a three-dimensional model of HSR train-track interaction. This model coupled the train and track so that both freight and HSR traffic could be modeled. The upper rail-sleeper- ballast structure was modeled as a sandwiched spring and dashpot system. Proper three-dimensional finite element models were applied to the embankment and subgrade to allow for propagation of transient stress waves and critical speed considerations. The cross section geometry and material properties remain constant with respect to the location along the track. All of this helps to allow for a computationally efficient algorithm. The analysis yielded significant differences in subcritical and supercritical speeds (as shown in Figure 1).

Analysis indicates that trains traveling at supercritical speeds will result in higher displacements than trains traveling at subcritical speeds. Along with the increase displacements, the displacement field exhibits distinct patterns in the soil. If these displacement fields are accurately predicted, the potential problems to track systems are significant. What is needed is field verification of the analytical studies to confirm the appropriateness of the computational method. For this reason, a field instrumentation project has been initiatied to measure the ground response to HSR trains passing over soft soil in the Great Swamp Management Area.

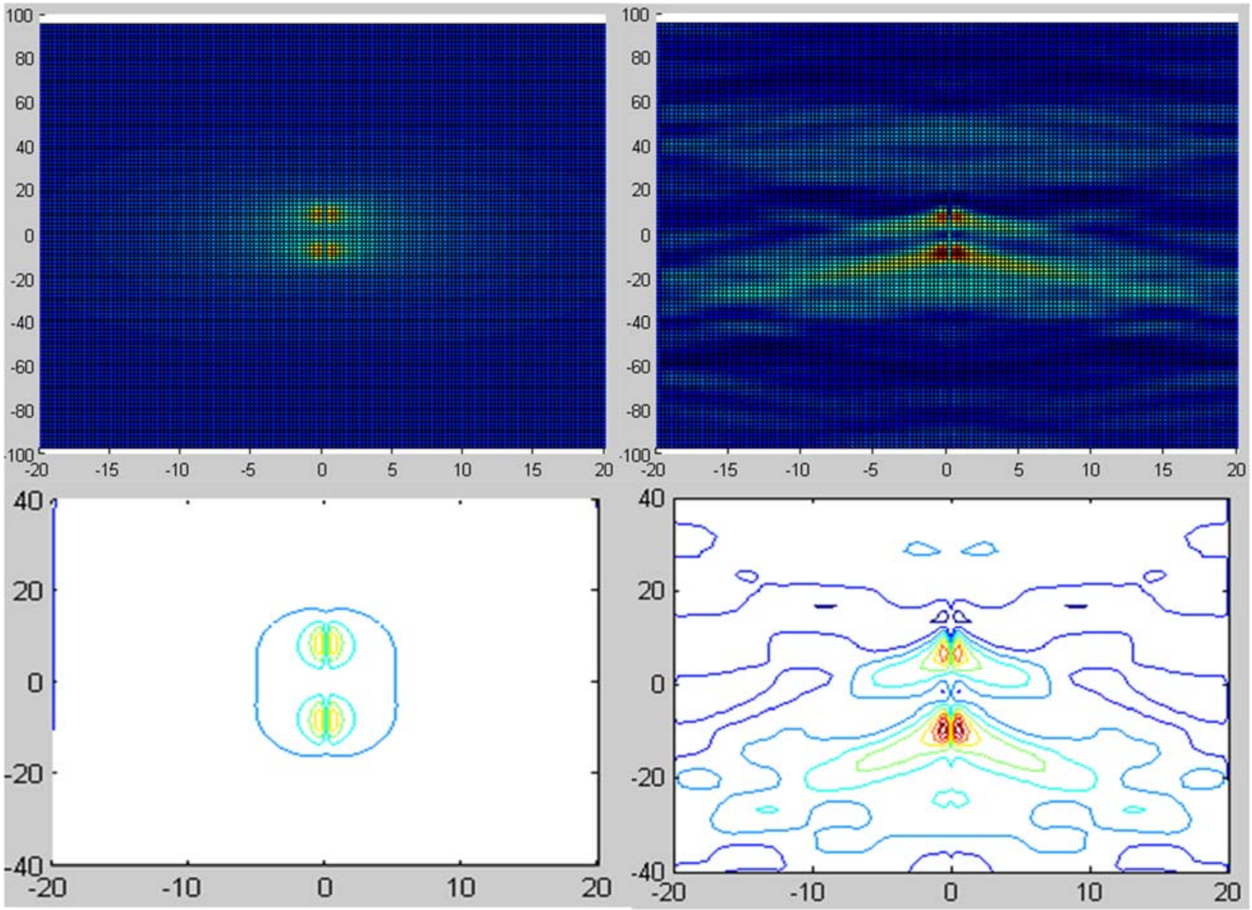

Figure 1. Soil surface deflections under subcritical speed (left) and supercritical speed (right) (Huang and Chrismer, 2013).

GREAT SWAMP MANAGEMENT AREA

Geologic Setting

The regional geology of New England (the northeastern portion of the United States) is dominated by Pleistocene glaciation (Kaye, 1960). The surficial geology in the general region where the Great Swamp is located is comprised entirely of various glacial deposits (moraines, kames, outwash, etc.) or swamp deposits from more recent Holocene. Coastline to the South was formed by the Charlestown Moraine, a terminal moraine, the southernmost extent of the last episode of glaciation The Great Swamp was formed as a part ancient glacial Lake Worden. Lake Worden was formed when glacial ice melted behind the Charlestown Moraine. As the glaciers retreated, a series of glacial deposits were left behind. In the area of the Great Swamp, the soil deposits are dominated by ground moraine, subglacial till, undifferentiated ice contact deposits and an organic swamp soil deposit as shown in Figure 2. The glacial ground moraine is a light colored deposit consisting uniform fine sand. As a result of the uneven glacial melting, the ground moraine has a hummocky topography that resulted in a variation in elevation and swamp deposits. The swamp deposits are completely underlain by this ground moraine. The ground moraine is a competent material for foundations as it is generally strong. Along with the ground moraine are subglacial till and undifferentiated ice contact deposits. These soils have many of the same characteristics of the ground moraine, but geomorphologically do not represent the same type of deposition. With respect to engineering characteristics, these materials are very similar and could be used in construction similarly.

The swamp deposits consist of normally consolidated dark organic clays and silts. Many of the swamp deposits are peaty. As a result, the deposits are soft and highly deformable. The thickness of the swamp deposits varies from 2 m to 8 m with most of the deposits having the lower range of thickness. It would not be uncommon to find peaty soil to have Rayleigh wave velocities as low as 50 m/s. It is because of these soft sediments that this section of the NEC is of great interest as an investigation site.

<u>Amtrak Northeast Corridor Study Area</u>
The Northeast Corridor (NEC) is a rail line owned primarily by Amtrak, which runs 760 km from Boston, Massachusetts to Washington, DC. This line has sections of class 8 track allowing speeds of 150 mph (241 kph). This line is not restricted to HSR trains (the Acela), but also serves regional passenger trains and limited commuter and freight trains. The NEC has the highest ridership of any of the passenger lines in the United States.

The subdivision of the NEC that is of interest of the critical speed study is a straight section of track that is currently classified for speeds up to 150 mph (241kph). A straight section of the NEC runs northeast/southwest through the northern section of the Great Swamp, Rhode Island just to the west of the town of South Kingston (Figure 2). Currently, this section of the NEC is a double track section that is used for both HSR trains and regional passenger trains. This section has required more frequent that average maintenance because of geometry issues. Ground penetrating radar (GPR) studies have indicated that there are sections of ballast and subballast that contain high water content sediments that could be contributing to the track geometry issues.

Three different sites were selected for study between MP 155 and MP 157. All three sites are located on sections of track underlain by swamp deposits. It should be noted that the ballast combined with the underlying granular fill material is typically about 2 m thick (as shown in Figure 3). The three sites were selected because they represent a tradeoff between a decreasing train speed in the southwesterly direction (due to an eventual curve) and a somewhat smaller fill thickness in the same direction which increases the stresses on the peat soil.. Sites 1, 2 and 3 (as shown in Figure 2) have typical train speeds of approximately 130 mph (209 kph), 140 mph (225 kph), and 150 mph (241 kph) respectively.

Figure 4 presents GPR profiles indicating the location of potentially problematic soils. Three sites were selected for instrumentation for the purpose of measuring the ground response resulting from HSR trains and regular passenger trains passing over the sites. It is hoped that the measured accelerations will be useful in evaluating the efficacy of using the modeling methods described earlier in this paper.

INSTRUMENTATION PLAN
The instrumentation plan is designed to measure both the displacements of the track system as well as the response of the ground around the track. In order to accomplish this, nine triaxial piezoelectric accelerometers will be placed as shown in Figure 5. The acceleration network is design so that the installation is temporary. The accelerometers are designed with a through hole that allows for an allen head cap screw to pass through. This will allow for a mounting plate to be attached to the sleeper permitting rapid installation and removal of the accelerometer. The six accelerometers that will be placed in soils adjacent to the track will be mounted on insertion devices that will allow for the accelerometers to be pushed into the soft soil and easily removed. The intention is that the accelerometers can be installed at multiple sites along the track to determine response due to geotechnical as well as spatial variations.

The accelerometer outputs will be recorded using conventional amplification, signal conditioning and data acquisition using a notebook computer. A video camera will be placed to be able to record the passing train so that the exact location of the train can be reconciled with the timing of the accelerograms. The instrumentation plan is designed so that readings can be taken at different times throughout the year. The purpose for this is to evaluate differences that may occur as a result of climatological variations throughout the year. It is likely that variations in temperature and precipitation will affect the stiffness of the ballast and near surface soils. In turn, this may have a significant impact on the surface wave velocities and propagation.

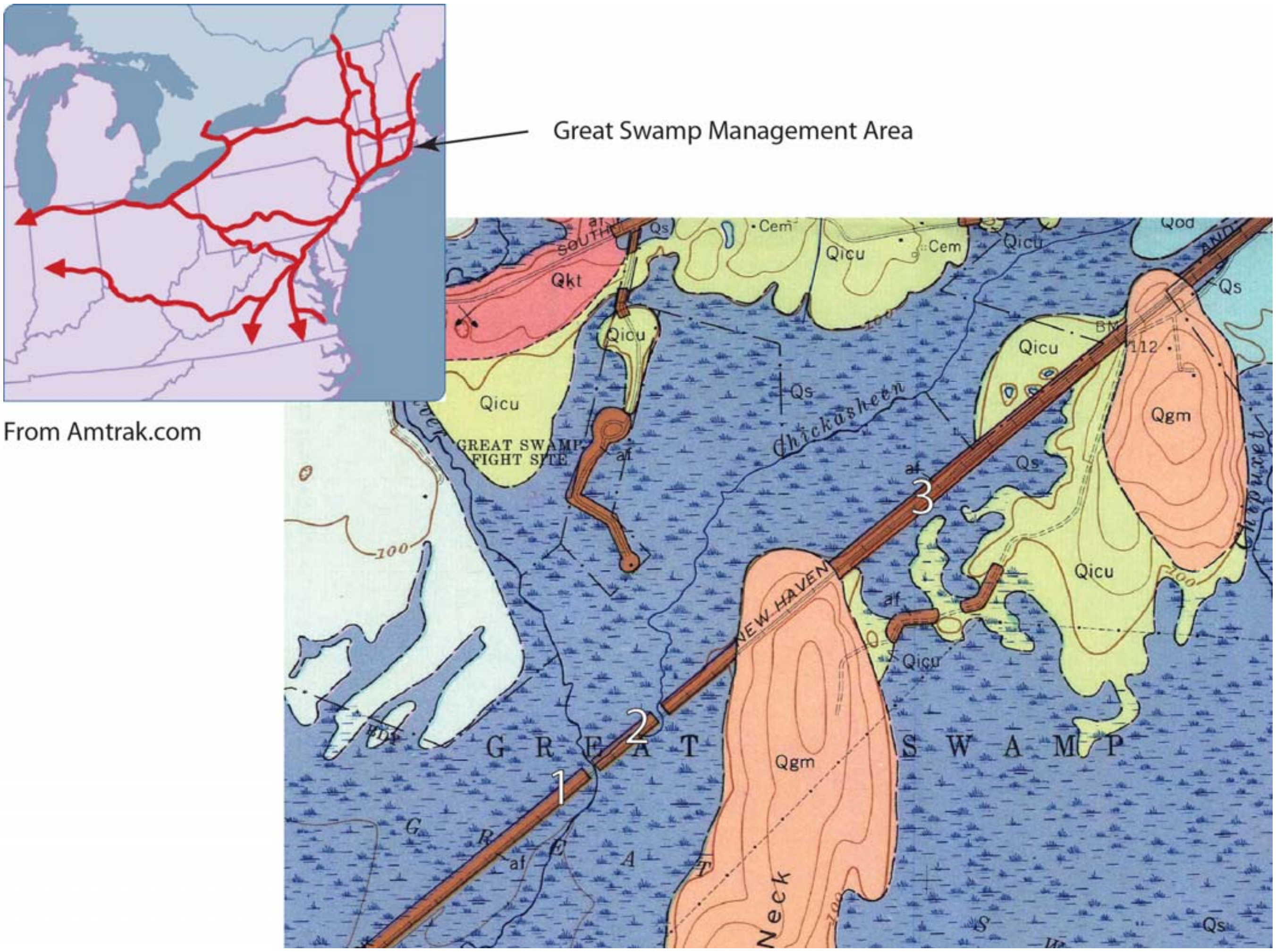

Figure 2. The Great Swamp Management Area is located in southern Rhode Island immediately to the southwest of the Kingston Station. The track passes over various Pleistocene and recent deposits. The deposits are identified by the following labels: Qgm—ground moraine deposits; Qicu—ice contact undifferentiated deposits; Qs—recent swamp deposits. Based on Kaye, 1960.

CONCLUSIONS

The dynamic response of soil to trains traveling at critical speeds has been modeled using various analytical tools. The results of various analyses indicate that these trains traveling at or near critical speeds can result in significant displacements with a characteristic pattern. These large displacements have the potential of resulting in damaging conditions to the track system. In order to properly assess the efficacy of the analytic methods, it is important to conduct field measurements of trains traveling at near critical speeds. Because of unique conditions, the instrumentation program has the potential to provide a means of verifying the various analysis techniques currently used to evaluate critical speed behavior and will lead to a better understanding of the phenomenon.

Figure 3. Northbound Acela train near MP 155 southwest of the Usquapaug River in the Great Swamp Management Area.

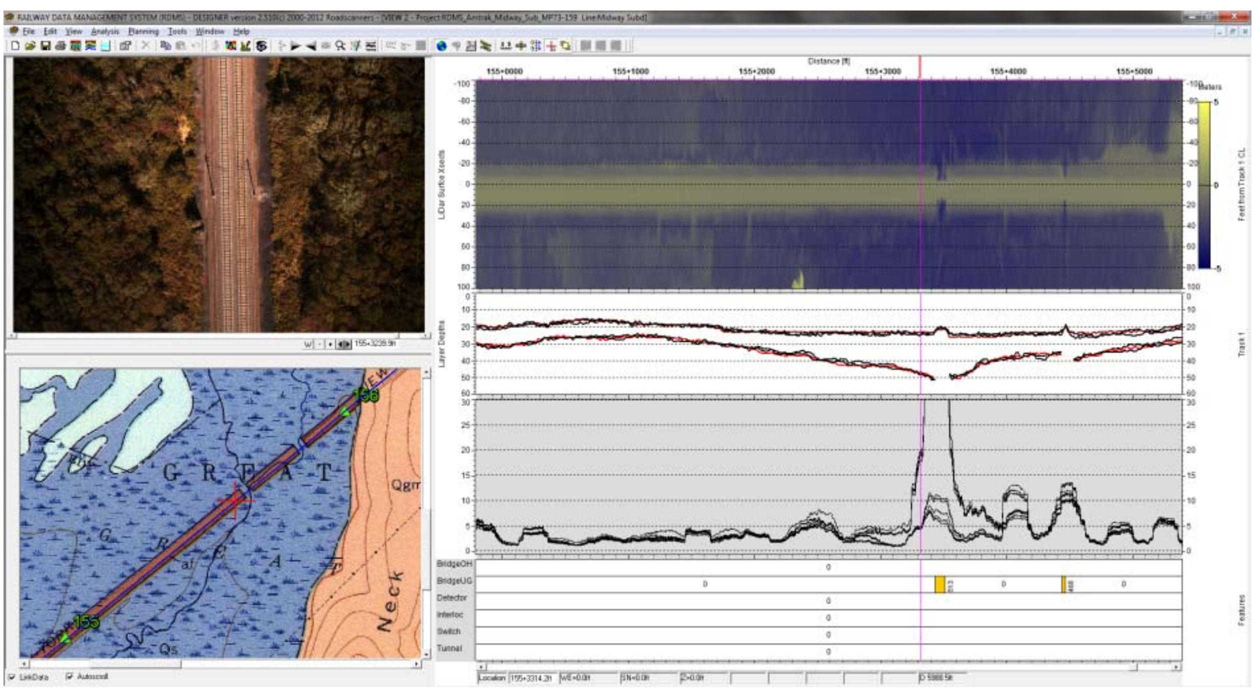

Figure 4. GPR data for milepost 155-156. Note the aerial photograph of the track section.

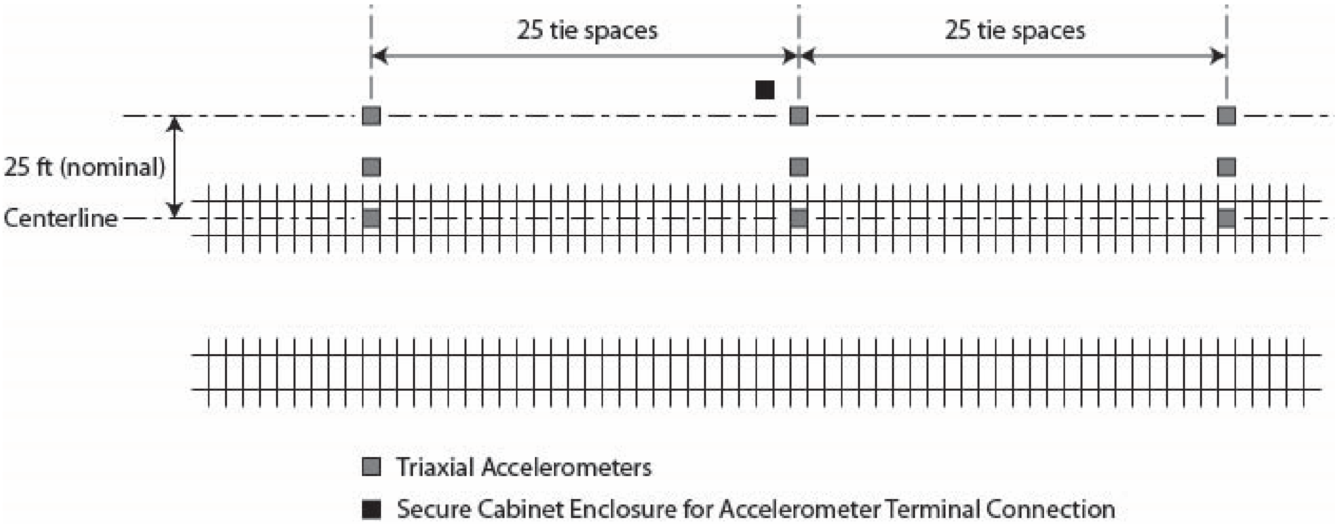

Figure 5. Layout of accelerometers for the purpose of measuring ground accelerations resulting from HSR trains traveling at supercritical speeds.

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