USE OF SEISMIC SURFACE WAVE TESTING TO ASSESS TRACK SUBSTRUCTURE CONDITION

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ABSTRACT

This paper describes the use of Spectral Analysis of Surface Wave (SASW) for characterizing rail track ballast and foundation layers. Surface wave testing on a rail track is more complicated than on soil sites or pavements due to the presence of large ballast void spaces, crossties, and rails as well as the complex variation of shear-wave velocity and Young's modulus with depth. Young's Modulus is presented for both clean and fouled ballast in wet and dry conditions using the results of surface wave testing and SASW. Young's modulus can be used to assess tie and track support at different locations, e.g. tie center and edge, under the applied loads. A portable surface wave system is described as well as its expansion to measure Young's Modulus under two ties in the same test.

INTRODUCTION

No established tool or system is available that quantitatively measure the engineering properties of the various track substructure layers, which can be used to assess track support and in numerical models. A two-year Federal Railroad Administration (FRA) sponsored research project is using seismic surface wave propagation principles to develop a portable system to assess track substructure (ballast and subgrade) condition. The resulting seismic system can be used in conjunction with track geometry car data and/or Ground Penetrating Radar (GPR) to measure engineering properties and determine the cause(s) of poor track performance, e.g., fouled ballast, degraded subgrade, and/or poor drainage. This research and test system is necessary because the track system is more complex than undeveloped sites or pavement applications where seismic techniques have been used successfully for years. The track system is more complex because of the presence of rails, crossties, large particles and voids in the ballast, and other railroad related equipment.

The most common engineering property used to evaluate substructure stiffness and perform numerical analyses is the modulus of deformation (i.e., Young's Modulus, E). Representative modulus values of the layered track substructure are important because the stiffness of individual substructure layers affect track displacements and wheel load distribution (Hay, 1982). Current methods for measuring Young's modulus include invasive cone penetrometer testing (Sussmann and Selig, 2000). Substructure modulus values have been estimated using an inverse analysis of field displacements with depth using the numerical software GEOTRACK (Sussmann and Selig, 2000; Mishra et al., 2014). However, the required instrumentation and setup to measure displacements with depth is expensive and time-consuming and the estimated ballast moduli can be too low because of the existence of a gap between the bottom of the tie and top of the ballast (Wilk et al., 2015).

Seismic methods represent a non-invasive alternative to measuring Young's modulus. Modulus values can be derived from the direct measurement of shear wave velocity (V_s) with a portable device described below. Values of V_s are used to calculate shear modulus, G, using Equation (1) and Young's modulus using Equation (2).

$$\boldsymbol{G = \rho * V_s^2} \tag{1}$$

$$\boldsymbol{E = 2 * G * (1 + \nu)} \tag{2}$$

where ρ = material density and ν = Poisson's Ratio.

Additionally, shear strength of the various layers in the track system can be estimated from the shear modulus (G) through empirical correlations or laboratory calibration. Values of moduli and shear strength can be used in numerical analyses to estimate the stresses and transient and permanent deformations induced in the track system by the estimated train traffic and impact of varying speed and number of cars. Without measurement of the shear wave velocity profile, the modulus, and shear strength of the track system materials are usually estimated which leads to inherent uncertainties in analyses and estimates of track performance and safety.

This paper describes the use of seismic wave methods to directly measure modulus values of ballast and subballast layers. Both clean and fouled ballast sites were tested herein in both dry and soaked conditions to develop ranges of Young's modulus for typical ballast conditions. Plans to modify current equipment to measure modulus under two ties during the same test as well as tie integrity are as presented.

SEISMIC SURFACE WAVE TESTING

In the last thirty years, seismic surface wave principles have been evaluated using several different approaches such as, Spectral Analysis of Surface Waves (SASW), for evaluation of various civil engineering and transportation infrastructure (Nazarian, 2012; Azari et al., 2014; Stark et al., 2014). The common goal with these approaches is to take advantage of the dispersive characteristics of surface waves in a layered system, such as a track system, to estimate modulus with depth. When seismic energy is coupled to the ground surface, three types of waves are generated, i.e., shear, compression, and Rayleigh. With careful consideration of the energy source and receiver configurations, surface wave interpretation techniques can be used to interpret the Rayleigh waves that propagate radially from the energy source. The depth of penetration of surface wave energy decreases exponentially with distance from the free surface and surface waves exhibit meaningful motion energy only to a depth of approximately one wavelength of the energy imparted on the ground surface. For engineering applications, e.g., seismic site classifications, surface waves have been employed to a depth of about 30 m (100 ft) to develop a shear wave velocity profile for the upper 30 m (i.e., Vs_{30}). For railroad applications, the depth of interest is usually less than 6 m (20 ft.), which is within the commonly used depth of seismic surface waves. The major challenge of the research was to develop a suitable means for coupling or anchoring the accelerometers to the ballast to measure the generated surface waves and understand the impact of track structure on wave propagation (Azari et al., 2014; Stark et al., 2014).

FIELD EQUIPMENT

Existing equipment at the University of Texas at El Paso (UTEP) has been used to develop effective means for coupling the accelerometers to the ballast to measure the propagation of seismic surface waves. The field equipment required for seismic wave testing consists of a computer based data acquisition system, an energy source, and two or more seismic wave sensors or receivers placed along a line on the ground surface. The requirement of the energy source is generation of surface wave energy over a range of frequencies so the three zones of dispersion can be defined (Nazarian, 2012). Each layer has a distinct acoustic impedance that acts to “disperse” the surface wave. This means that different frequency components of the surface wave propagate at different speeds, called phase velocities. The phase velocities are calculated as a function of frequency. The energy source is usually impulsive, e.g., a small hammer hitting a small strike plate. This project is currently using accelerometers with a natural frequency of 3000 Hz to receive or measure the surface wave with time.

If only the ballast and subballast are of interest, i.e., shallow depth, a hand-held device can be used and the resulting device used is termed the Ballast Seismic Property Analyzer (BSPA) and is displayed in Figures 1 and 2. The energy source is the left most vertical cylinder in Figure 1 and the other two vertical cylinders are sensors to receive the seismic surface waves. The BSPA device can be used to measure the ballast modulus at various locations under or near a single tie including the tie edge (Figure 1), tie center (Figure 2), or parallel to the tie to measure the ballast modulus in the crib (Figure 2),.

Figure 1: Photograph of BSPA measuring ballast modulus under the edge of a timber tie

Figure 2: Photograph of BSPA measuring ballast modulus under a concrete tie

Additionally, the BSPA device can measure the modulus of timber and concrete ties by placing the device directly on the tie (Figure 3). It is anticipated this will be a quick and portable method for assessing tie integrity because the modulus of a damaged tie will be lower than the modulus of an intact tie. The presence of cracks within a damaged tie lowers the shear wave velocity (V_s) because it takes longer for shear waves to pass a discontinuity than in a fully continuous tie. The tie is also important for interpreting the shear modulus of the ballast because the wave form associated with the seismic waves passing through the tie is known and can be differentiated from the waves passing through the ballast under the tie.

Figure 3. **Photograph of the BSPA system measuring the modulus of a timber tie**

BALLAST MODULUS

Field measurements of various track systems in a companion research effort (Stark and Wilk, 2014; Wilk et al., 2015), show most transient tie vertical displacements consist of the following three components of movement (see Figure 4): (1) closure of a gap between the tie bottom and ballast surface (δ_{gap}), (2) initial non-linear load-displacement behavior of the ballast (δ_{seat}), and (3) non-linear displacement of ballast to resist the applied loads ($\delta_{mobilized}$).

The contribution of each displacement component to the total transient displacement was determined by plotting measured peak wheel load and corresponding transient tie displacements in a load-displacement diagram similar to the diagram shown in Figure 4 for a variety of sites (Wilk et al., 2015). Based on these field measurements, Figure 4 presents a conceptual model of the tie load-vertical displacement response under either high-speed passenger or freight traffic. Formation of a tie-ballast gap is the key feature of the conceptual model and while a gap may not be detrimental or significant as shown below, it is usually present under most, if not all, ties after passage of a single train due to the initial loose or uncompacted nature of ballast. For example, newly laid or recently tamped track has loose ballast that is in intimate contact with the overlying tie as shown in the upper left schematic diagram in Figure 4 for no wheel passes. As the first train loads the track structure, the ballast particles rearrange into a more compact state (δ_{seat}) and displace under the applied load ($\delta_{mobilized}$). Because ballast behavior is inelastic and stress dependent, the particles do not return to their initial position after the first train passage resulting in a gap below the tie as shown in the upper right schematic in Figure 4 for greater than or equal to one (1) wheel pass. In other words, after the first train pass the ballast does not elastically rebound to its initial position because ballast particle rearrangement and the ballast being in a more compact state. After the train passes, the track is supported by ties that settle the least and the rail stiffness then pulls the tie back up creating a gap between the bottom of the tie and ballast as shown in the upper right schematic diagram in Figure 4 for greater than or equal to one (1) wheel pass.

The solid line in Figure 4 represents the theoretical tie load-displacement behavior with a gap between the tie bottom and ballast (δ_{gap}). As the tie is loaded, the gap closes and the ballast starts resisting the applied load by mobilizing shear resistance from ballast particle friction and interlocking. Tie displacement during shear mobilization of the ballast is represented by δ_{seat} and the load to fully mobilize the ballast is defined as the tie seating load. Any tie displacement after seating occurs ($\delta_{mobilized}$) is due to displacement of the ballast and underlying soils to resist the applied wheel load and the tie should displace linearly with increasing applied load in accordance with the mobilized stiffness (k_{mob}) of the ballast and underlying soils. Because the ballast stiffness is mobilized, the corresponding tie displacement is referred to as the mobilized displacement or $\delta_{mobilized}$.

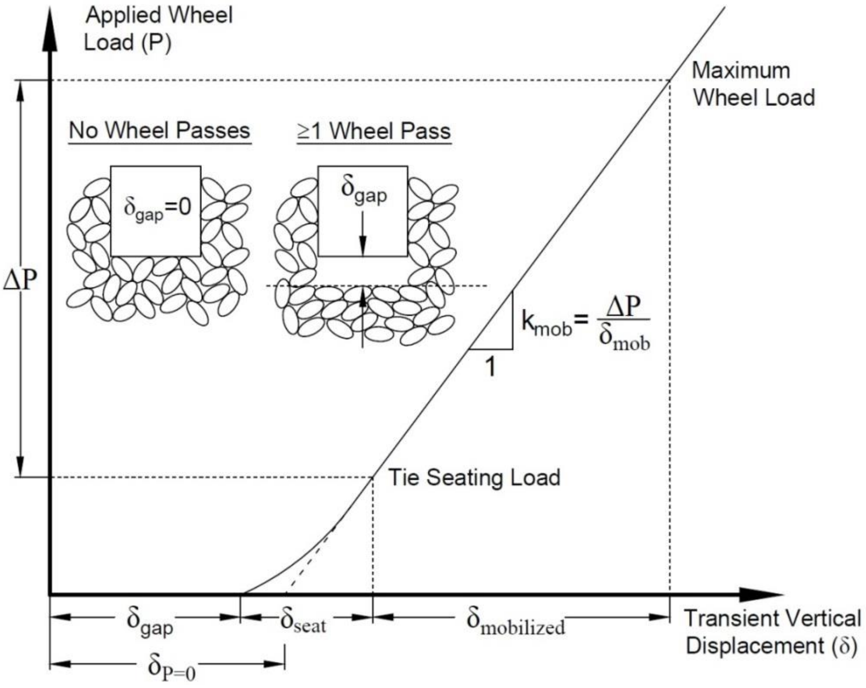

Figure 4. Transient vertical displacement behavior of a tie with a gap under applied wheel load.

This model illustrates the interest in and importance of ballast modulus below one or more adjacent ties. Knowing this process, it can be inferred that development of a tie-ballast gap is partly the result of the initial loose or uncompacted ballast. By testing the ballast density under the tie after tamping or track remediation, railroad companies can verify ballast density is sufficient to prevent the formation of tie-ballast gaps in regions that typically experience reoccurring track geometry issues such as bridge transition zones. The required ballast density can be determined through large-scale direct shear laboratory tests as described by Stark et al. (2014).

FIELD TESTING

Preliminary testing with the BSPA device involved measuring the ballast modulus of both clean and highly fouled ballast under both dry and wetted conditions. Testing occurred at the Transportation Technology Center (TTC) in Pueblo, Colorado on 20 October 2013 and 18 September 2014.

Clean Ballast

The first site tested at TTC was a clean ballast section of track. The same section of track was tested in both dry and wetted conditions to investigate the effect of moisture content on clean ballast. Figure 5 shows the wetting of the track section by the TTC fire department with a hose.

Figure 5: Photograph of wetting of a section of clean ballast track

As expected, ballast wetting did not significantly change the measured ballast modulus because water did not change the strength or stiffness of the ballast aggregate. The modulus values range from 200 to 275 MPa (30 to 40 ksi) as shown in Table 1. These values are generally within the range of published results of unfouled ballast modulus (Selig and Waters, 1994).

Table 1: Measured Ballast Modulus from Seismic Testing

Ballast Type	Modulus [MPa]	Modulus [ksi]
Clean – Dry and Wet	200 – 275	30 – 40
Fouled – Dry	340 – 380	50 – 55
Fouled – Wet	135 – 170	20 – 25

Fouled Ballast

A significant problem affecting the railroad track substructure is fouled ballast and its impact on track support. Site investigations by the authors show tie-ballast gaps are present at highly fouled ballast sites because of the increased substructure settlement and reduced tie support. Laboratory triaxial compression tests also show dry fouling increases the permanent displacement of ballast (Qian et al., 2014), likely due to a decrease in shear strength and/or modulus. For example, Figures 6 and 7 show photographs of a wet, fouled section of track where substructure settlement underneath the tie produced a tie-ballast gap of about 25 mm (1 inch) in height. The fouling was isolated to one or two ties (see Figure 6) but enough fouling was present for the site to experience mud pumping. Figure 6 shows mud covering the rail and ties because of the dynamic loads from the passing freight trains increasing the pore pressures underneath the tie causing water to repeatedly shoot onto the rail and tie. Figure 7 shows significant ballast settlement away from the tie due to ballast and fouling compression. The resulting tie-ballast gap is large enough to push a stick underneath the tie as shown in Figure 7.


12/03/2013

Figure 6: Photograph of wet, fouled ballast.


12/03/2013

Figure 7: Photograph of a gap underneath a tie in a wet, fouled ballast section of track.

Using the BSPA device, the differences in fouled ballast modulus are compared for both dry and fully wetted conditions. Similar to the clean ballast site, measurements prior to and after wetting were performed at the exact same track location at the TTC facility. The track site was wetted using a hose and allowed to soak for about 15 minutes prior to testing (see Figure 8) so the modulus results reflect wetting but not full saturation which may occur during a long precipitation event.


10 28 2013

Figure 8: Photograph of the full soaking of a section of fouled ballast track

The dry and wet fouled ballast modulus values show significant difference with the modulus decreasing from a range of 340 to 380 MPa (50 to 55 ksi) when dry to a range of only 135 to 170 MPa (20 to 25 ksi) when wetted. This is a decrease of almost 50% and will have significant implications for transient vertical displacements and track performance. More importantly, this decrease in modulus in fouled sections of track will occur repeatedly because of the regular wet and dry cycles (rainfall or snowfall) that a track can be subjected to while in service. This will result in track behavior varying with time. For example, after rainfall the ballast will experience larger transient (and permanent) vertical displacements as the ballast particles settle and are pushed further into the substructure than under a dry condition. This will produce a larger gap between the bottom of the tie and top of the ballast that will not recover. After drying, the tie-ballast gap will remain but subsequent loading will cause the tie to impact a much stiffer substructure and possibly cause tie degradation. The cycling of these two conditions can accelerate the deterioration of both the track super- and substructure requiring railroads to remediate frequently.

FUTURE WORK

Because the modulus underneath railroad ties is important for diagnosing track performance, modifications of the BSPA device will extend the device so the ballast and subbalast modulus can be measured under two ties without moving the device. It is anticipated the first sensor will be located 50 cm (20 inches) from the source and the second sensor will be located 100 cm (40 inches) from the source (see Figure 9). This will allow the ballast modulus to be measured underneath a tie along with a deeper measurement that includes the subballast.

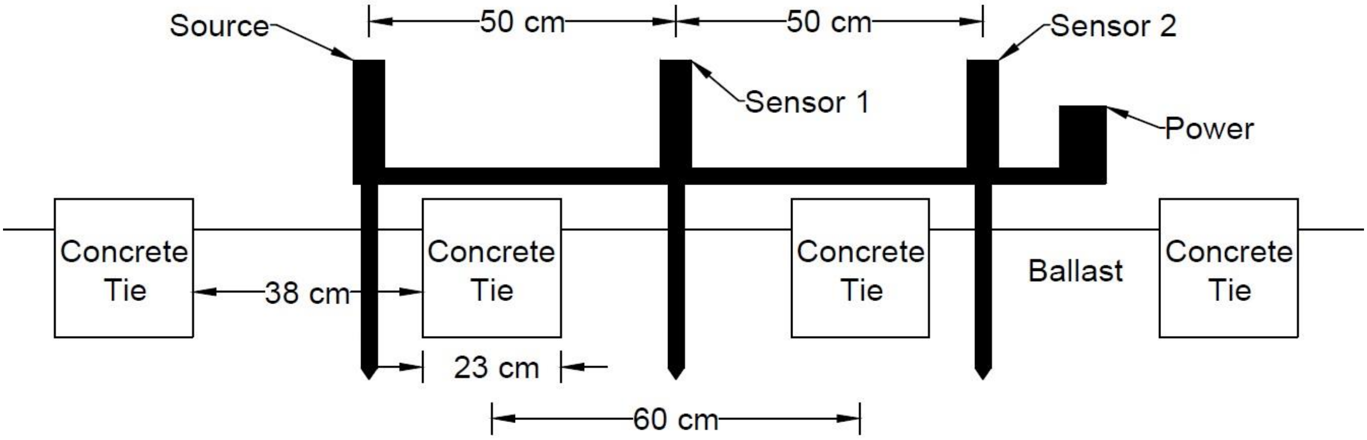

Figure 9: Diagram of future modifications to the BSPA device.

SUMMARY

This paper presents a non-invasive measuring technique to estimate the modulus of the ballast and subballast layers using seismic Raleigh waves. The current portable BSPA device can measure the ballast modulus underneath both the edge and center of a single tie and also within the crib. This is important for track analyses, numerical simulations, estimating ballast shear strength, determining whether the ballast density underneath the ties is high enough to prevent the enlargement of the tie-ballast gap, and whether the ballast should be disturbed during remedial operations. The device is expected to be modified to measure the ballast modulus under two ties instead of one without moving the device. The device will also be used to evaluate tie integrity by testing only the tie.

The BSPA device measured ballast modulus in both dry and fully wetted conditions. It was found that moisture content had little effect on the modulus of clean ballast (200 – 275 MPa) while soaking had a significant effect on fouled ballast. However, the measured modulus decreased by about 50% from a range of 340 – 380 MPa to 135 – 170 MPa upon wetting with a fire hose. This change in modulus, and therefore track behavior, can facilitate the development of tie-ballast gaps because of the increased transient and permanent displacements of the fouled ballast when wet.

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