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I REALLY LIKE THIS TITLE!!!!
EVALUATING FOULED BALLAST USING SEISMIC SURFACE WAVES

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ABSTRACT

This paper presents the equipment and Spectral Analysis of Surface Wave (SASW) approach for non-invasively characterizing railroad track ballast and foundation layers. Surface wave testing on a railroad track is more complicated than that on soil sites or pavements because of the presence of ballast, crossties, and rails as well as the complexity of ballast-soil foundation structure in terms of the variation of shear-wave velocity with depth. Using portable SASW equipment, the Young's Modulus of the ballast was calculated for both clean and fouled ballast in wet and dry conditions. In addition, the local modulus is determined at different locations under the tie, e.g. tie center or edge, to investigate modulus variation and tie support under a single tie. Expansion of the system to measure the modulus under two adjacent ties is also discussed and may be suitable for evaluating ballast performance under §213.103, which requires ballast to perform the following serviceability functions: (1) transmit and distribute the load of the track and railroad rolling equipment to the subgrade; (2) restrain the track laterally, longitudinally, and vertically under dynamic loads imposed by railroad rolling equipment and thermal stresses exerted by the rail; (3) provide adequate drainage for the track; and (4) maintain proper track crosslevel, surface, and alignment".

INTRODUCTION

No established tool or system is available that quantitatively measures the engineering properties of the various track substructure layers, which are necessary to assess track support and execute numerical models. A two-year Federal Railroad Administration (FRA) sponsored research project is using seismic surface wave propagation principles to develop a portable and non-invasive system to assess track substructure (ballast and subgrade) conditions in areas identified as potentially problematic by track geometry and Ground Penetrating Radar (GPR) data. The resulting seismic wave system can be used 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 was 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 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 [1]. Current methods for measuring Young's modulus include invasive cone penetrometer testing [2] and obtaining large samples of ballast and trying to reconstitute the sample to match field conditions for laboratory testing. Substructure modulus values also have been estimated using an inverse analysis of field displacements with depth using the numerical software GEOTRACK and FLAC [2,3]. However, the required instrumentation and setup required 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 [4].

Seismic methods represent a non-invasive alternative to measure shear wave velocity (V_s) and estimate Young's modulus. Values of V_s are used to calculate shear modulus, G, using Equation (1) and then Young's modulus using Equation (2).

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

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

where ρ is the material density and ν is 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 [reference????]. 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 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 subsurface 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 surface wave methods to directly measure V_s of the 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 adjacent ties during the same test as well as tie integrity are also 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 [5-7]. 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 V_s profile for the upper 30 m (i.e., $V_{s,30}$). 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 is to develop a suitable means for coupling or anchoring the seismic receivers, i.e., accelerometers, to the ballast to measure the generated surface waves and understand the impact of track structure on wave propagation [6-7].

SEISMIC SURFACE WAVE TESTING

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 accelerometers placed along a line on the ballast 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 [5]. 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 waves with time.

If only the ballast and subballast are of interest, i.e., shallow depth of interest, a hand-held device can be used because a large energy source is not needed. The hand-held device is termed the Ballast Seismic Property Analyzer

FIGURE 1 – PHOTOGRAPH OF BSPA MEASURING BALLAST MODULUS UNDER THE EDGE OF A TIMBER TIE

(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 record 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 – 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 V_s because it takes a longer time 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 BSPA MEASURING MODULUS OF A TIMBER TIE

BALLAST MODULUS

Field measurements of various track systems in a companion research effort [4,8], 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 [4]. 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 after placement. 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 passes 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 of ballast particle rearrangement and the ballast being in a denser state. This can result in ballast settlements up to 20 mm (0.8 inches) from the first train after tamping [9]. After the train passes, the track is supported by ties that have the smallest tie-ballast gap 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 that occurs after seating ($\delta_{mobilized}$) is due to displacement of the ballast and/or underlying soils to resist the applied wheel load. Field studies show a linear relationship [8] between increasing applied load and displacement 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 $\delta_{mobilized}$.

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 modulus/density directly under the tie after tamping or track remediation, railroads can verify ballast density is sufficient to prevent formation of a larger and detrimental tie-ballast gap in regions that typically experience reoccurring track geometry issues such as bridge transition zones. The required ballast modulus/density can be determined through field seismic surface waves and/or large-scale direct shear laboratory tests [10].

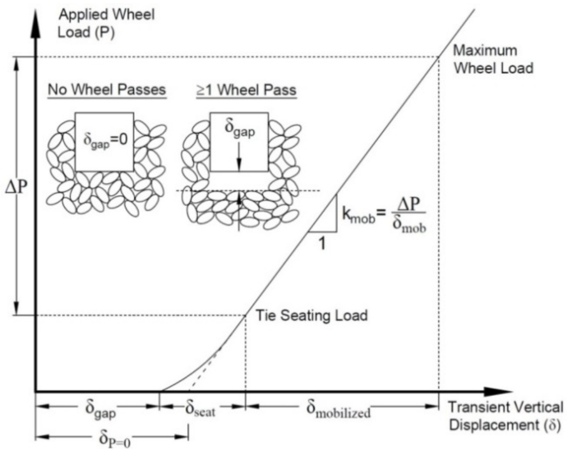

FIGURE 4 – TRANSIENT VERTICAL DISPLACEMENT BEHAVIOR OF A TIE WITH GAP UNDER APPLIED WHEEL LOAD (GRAPH LOOKS BLURRY SO REPLACE WITH BETTER IMAGE????)

FIELD TESTING

Preliminary field testing with the BSPA device involved measuring the ballast modulus of both clean and highly fouled ballast under both dry and wetted conditions. This 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 is 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.

As expected, ballast wetting did not significantly change the measured ballast modulus because water did not change the strength or stiffness of the clean ballast. 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 modulus values for clean ballast [11,12]. The authors are unaware of any published resilient modulus values comparing wet and dry states of fouled ballast however, an increase in permanent deformation has been noted for wet, fouled ballast in laboratory tests [13].

FIGURE 5 – PHOTOGRAPH OF WETTING OF A SECTION OF CLEAN BALLAST

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 railroad track substructure is fouled ballast and its impact on track support and geometry. Site investigations [4, 8, 9] show tie-ballast gaps are present at highly fouled ballast sites because of the increased ballast and substructure settlement and reduced tie support. 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-water pressures in the fouled ballast 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. Laboratory triaxial compression tests show even dry fouling also increases the permanent displacement of ballast [13,14] because of a likely decrease in particle frictional strength, shear strength, and/or modulus [15].

FIGURE 6 – PHOTOGRAPH OF WET, FOULED BALLAST

FIGURE 7 – PHOTOGRAPH OF A GAP UNDERNEATH A TIE IN WET, FOULED BALLAST SECTION OF TRACK

Using the BSPA device, the differences in fouled ballast moduli 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 the fouling material allowed to soak for about 15 minutes prior to testing (see Figure 8) so the modulus results reflect wetting but not full saturation of the fouling material which may occur during a long precipitation event.

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. This difference in fouled ballast behavior due to wetting has also been observed in ballast box experiments [13] and monotonic triaxial tests [14]. More importantly, this decrease in modulus in fouled sections of track can occur rapidly after a precipitation event and vary seasonally 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 and possibly result in a situation where track safety standards may be unsatisfied only during wet periods. Additionally, the change in stiffness from wet to dry fouled ballast can affect track components in the superstructure by increased impact loads, load redistribution, and excessive transient and permanent deflections.

FUTURE WORK

Because the modulus underneath railroad ties is important for diagnosing track performance, modifications of the BSPA device include extending the device so the ballast and subballast modulus can be measured under at least 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 will include the subballast and possibly the upper portion of the subgrade. This can give insight into changes in ballast and subballast condition between depths of 50 to 100 cm (20 to 40 inches)

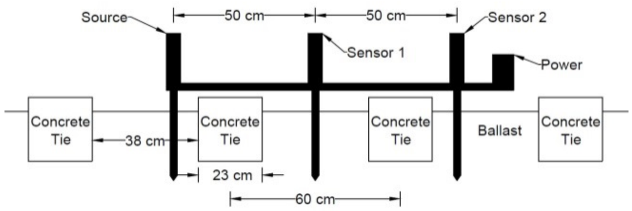

FIGURE 9 – DIAGRAM OF FUTURE MODIFICATIONS TO BSPA DEVICE

SUMMARY

This paper describes a non-invasive measuring technique to estimate the modulus of the ballast and subballast layers using seismic Raleigh waves. The 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 sufficient to prevent enlargement of the tie-ballast gap, and whether the ballast should be disturbed during remedial operations to achieve a greater density. The BSPA 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 placing the device on only the tie.

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

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