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SEISMIC TESTING FOR TRACK SUBSTRUCTURE (BALLAST AND SUBGRADE) ASSESSMENT FOR PASSENGER/FREIGHT CORRIDORS

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ABSTRACT

This paper presents the research framework and preliminary findings from a recently started Federal Railroad Administration (FRA) sponsored research project at the University of Illinois at Urbana- Champaign on developing and using seismic wave propagation principles to develop a track substructure (ballast and subgrade) condition assessment system. This condition assessment system will be used to evaluate track safety and to predict inspection intervals. This research is needed because there is no tool or system available that quantitatively measures the mechanics based properties of the layers comprising a track system. These mechanics based properties are shear modulus, modulus of deformation (Young's modulus), and shear strength that can be derived from direct measurement of the shear wave velocity profile. Currently the modulus and shear strength of the track system materials are usually estimated which leads to uncertainty in the numerical analyses and estimates of track safety.

INTRODUCTION

This new two year Federal Railroad Administration (FRA) sponsored research project is using seismic wave propagation principles to develop a track substructure (ballast and subgrade) condition assessment system to evaluate track safety and inspection intervals. This research is needed because currently there is no tool or system available that quantitatively measures the mechanics based properties of the layers comprising a track system that are required for numerical analyses. These mechanics based properties are derived from direct measurement of the shear wave velocity, V_s, profile. Values of V_s can be used to calculate shear modulus, G, (see Equation 1), modulus of deformation (Young's modulus, E) (see Equation 2). Shear strength of the various layers in the track system can be estimated from the shear modulus through a laboratory calibration. The values of moduli and shear strength are needed to perform numerical analyses to estimate the stresses and permanent deformations induced in the track system by the loads applied by current train traffic and the improved safety if traffic loads are reduced in problem areas. More specifically, the V_s derived parameters can be used to numerically model problematic areas to determine the cause(s) of poor track performance or safety and estimate future bearing capacity, dynamic response, and settlement of the track system due to future train traffic. This information can used to assess track safety with additional train traffic and operating parameters, e.g., speed and weight. Without measurement of V_s, the modulus and shear strength of the track system materials are usually estimated which leads to uncertain analyses and estimates of track safety.

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

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

where:
G = shear modulus
E = Young's modulus
V_s = shear wave velocity
ρ = material density
ν = Poisson's Ratio

The main objective of this project is to develop a system for rapidly, non-destructively, and quantitatively assessing the engineering properties of the track substructure (ballast and subgrade). The system will be developed under RailTEC at the University of Illinois at Urbana- Champaign (UIUC) with assistance from the University of Texas at El Paso and the University of Massachusetts at Amherst. The resulting system will be used in conjunction with Ground Penetrating Radar (GPR) to not only measure the engineering properties but also to determine the cause(s) of the potential problem areas, i.e., degraded track or reduced performance. Seismic wave propagation is the preferred method for measuring these mechanics based properties, i.e., modulus and shear strength, because of the complex nature of the track system. This research is necessary because the track system is much more complex than undeveloped sites or pavement applications where seismic techniques have been used successfully because of the presence of the rails, crossties, ballast, and other railroad related equipment. The largest anticipated complexity is developing a suitable means for coupling the sensors to the ballast to effectively measure the seismic waves. A following section of this paper details the initial spacing of the seismic sensors from the vibration source to develop a V_s profile through the track system that can be used to estimate modulus and shear strength in the layers that are of interest in the track system.

PREVIOUS NON-DESTRUCTIVE TESTING OF TRACK SUBSTRUCTURE

Ground Penetrating Radar (GPR) is used to assess track substructure condition, e.g., degree of ballast fouling, increased moisture, changes in material type, and moisture pockets [1,2,3,4,5]. GPR is used primarily because it is a rapid and nondestructive technique that has evolved over the past two decades to detect ballast contamination [1]. GPR is usually mounted on a moving platform to inspect the substructure at commonly used track inspection speeds. After processing, GPR derived data can be displayed in easy to read color-coded amplitude plots to identify anomalies or changes in the ballast and subgrade materials [1].

The seismic wave techniques described below will be used in conjunction with GPR to develop mechanics based properties for the track substructure in problematic or potentially problematic areas. In other words, GPR will be used to delineate problematic areas and then seismic wave techniques will be used in the problematic area to measure V_s with depth to determine modulus and shear strength with depth in the area. The modulus and shear strength properties can then be used directly and/or with numerical models to determine the depth of ballast fouling, modulus change, deformation, and moisture changes to assess bearing capacity and rate and magnitude of deformation under future train traffic. This system also could be used to investigate the cause of a derailment by measuring the engineering properties with depth in the derailment area and predicting the deformations of the subgrade and track system that resulted in the derailment under the applied train loading using numerical methods. This would provide the FRA with the necessary mechanics-based input parameters to analyze derailments and determine why a derailment occurred, e.g., what layer(s) contributed to the derailment, when the track system starting deviating from normal performance, and how the track system deformed prior to derailment.

Seismic wave techniques also can be used to augment GPR results and facilitate use of GPR results. For example, seismic techniques can provide quantitative values of engineering properties for the ballast and subgrade that can assist with the interpretation of GPR results in the area. For example, it is envisioned that the measured values of V_s can be used to calibrate the GPR results to delineate areas of high and low modulus materials which can be used with the location of areas of increased moisture.

In summary, seismic wave techniques will augment GPR technology by developing engineering properties for sites identified by GPR as potentially problematic. The seismic wave techniques will complement GPR by providing V_s depth, modulus, and shear strength with depth in the problematic area. These parameters will assist the numerical modeling and assessment of the problem areas identified by GPR.

SEISMIC WAVE TESTING

Seismic surface wave principles are being used herein to estimate the shear wave velocities of different layers under the track system. In the last thirty years, these principles have been implemented in several different approaches such as the Spectral Analysis of Surface Waves (SASW) and Multi-channel Analysis of Surface Waves (MASW) for evaluation of various civil engineering and transportation infrastructure. The common goal with these approaches is to take advantage of the dispersive characteristics of surface waves in a layered structure, such as a track system (see Figure 1). 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, the focus of the surface wave interpretation techniques is on 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. Surface waves have been commonly employed to a depth of about 30 m (100 ft) for seismic site classifications based on the average shear wave velocity of the upper 30 m or V_{s30}. For railroad applications, the depth of interest is probably around 6 m (20 ft) or less which is within the commonly used range of seismic waves. This background reinforces that one of the major challenges of the research is to develop a suitable means for coupling or anchoring the geophones to the ballast to measure the generated seismic waves.

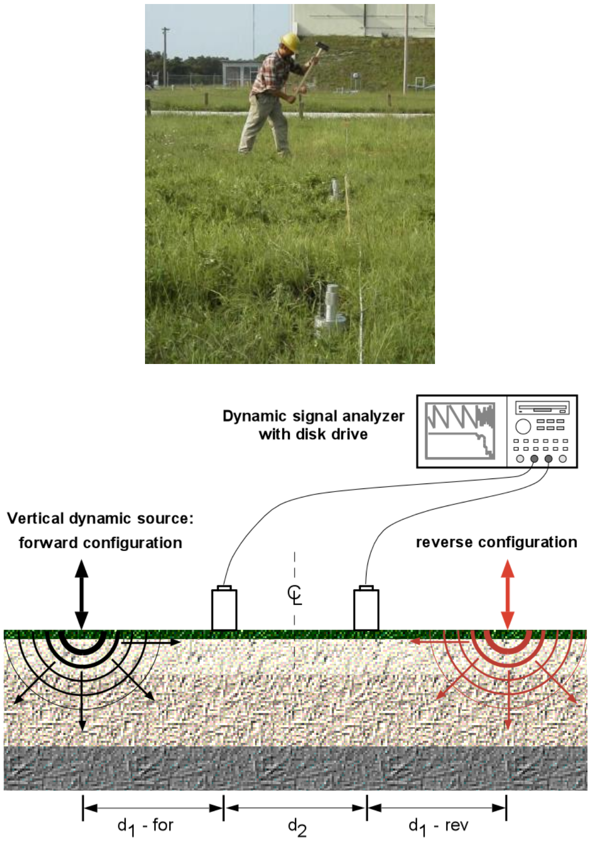

FIGURE 1 – SPECTRAL ANALYSIS OF SURFACE WAVES TESTING AND DATA ACQUISTION (PHOTO AND DIAGRAM FROM WWW.GEOVISION.COM WEBSITE)

Field Equipment

The dispersion curve (variation in surface wave velocity with frequency or wavelength, see Figure 2), is the raw data measured during surface wave testing. As such, one of the areas of intense research and development has been in recommending accurate and robust protocols to measure the dispersion curve. Most differences among different surface wave approaches (SASW, MASW, etc.) stem from difference in dispersion curve measurement. Irrespective of the approach considered, there are common best practices that should be used to obtain the dispersion curve for a track system, which are being evaluated in this study.

The field equipment required for seismic wave testing consists of an energy source, two or more seismic wave sensors or receivers placed along a line on the ground surface, and a computer based data acquisition system. The requirement of the energy source is generation of surface wave energy over a range of frequencies so the three zones of the dispersion curve in Figure 2, i.e., low, medium/transitional, and high frequency, can be defined. Each layer has a distinct acoustic impedance that acts to "disperse" the surface wave. This means that different frequency components of the surface wave pulse 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 sledge hammer hitting the ground surface of rail. Velocity transducers, i.e., geophones, are the most common receivers used in geotechnical applications. This project is currently using geophones with a natural frequency of either 4.5 Hz or 1 Hz because they have been effective to a depth of 30 m (100 ft) but other geophones will be considered to develop the optimal configuration for seismic testing of track systems.

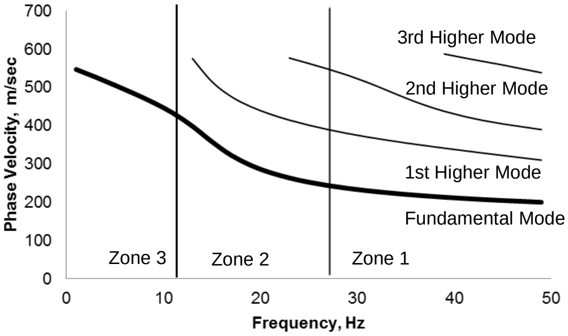

FIGURE 2 – EXAMPLE DISPERSION CURVES FOR A TYPICAL GEOTECHNICAL SITE

SASW Dispersion Curve Development

The main result of the field surface wave testing is measurement of a series of time records by the receivers that are processed to develop a dispersion curve. In the SASW method, each pair of time records is analyzed in the frequency domain to develop individual dispersion curves and then they are combined to develop a representative dispersion curve for the layered system.

The SASW approach can be tedious if a two-channel system is used but it can be used to develop a representative dispersion curve for depths of 100 ft (30 m) or greater by simply changing the energy source. The advantage of the SASW method is the data processing is understandable and readily apparent so the reliability of the data can be judged in real time as is currently done in the Seismic Pavement Analyzer (a commercially available device for conducting SASW on pavements) [6]. The current state of practice is to utilize a multi-channel recording system to collect up to sixteen (16), not two, channels of time records simultaneously which is the focus of multi-channel analysis of surface waves, which is discussed below.

MASW Dispersion Curve Development

MASW and SASW techniques are being used to investigate the improvement, if any, that MASW provides over SASW results. MASW data collection is based on multiple wave signals being collected on the ground surface along an equally-spaced linear array of receivers from the wave source (such as an impact event). The set of signals can be obtained using several receivers and a single wave source, or a single receiver and multiple wave sources. A type of 2-D Fourier transform procedure is applied to transform the data set from the spatial offset-time domain to the frequency-phase velocity domain. This type of data presentation allows the dispersive nature of the fundamental and higher order wave modes, contained in the same signal, to be distinguished. The two main advantages of MASW over SASW interpretation techniques are: (1) results are less sensitive to environmental noise because of the redundancy in the time records, and (2) assumption that the surface energy is focused in the fundamental mode of the Rayleigh wave is not required. However, the two main practical limitations of MASW are: (1) a dozen or more time records are necessary which increases set up time and system cost and (2) additional consideration of the source-receiver array is required to obtain reliable data for both shallow and deep strata.

In summary, MASW is also being utilized during this study and may overcome some of the limitations of the two-channel SASW method and be desirable for railroad applications. To facilitate use of MASW in this project, and by utilizing multi-channel data collection with the SASW method, it may be possible to reduce the timing and number of sensor spacings by simply using multi-channel data collection with the SASW method instead of having to install twelve or more receivers as is usually required for MASW as discussed below.

Estimation of Shear Wave Velocities of Layers

After a representative dispersion curve is obtained with either SASW or MASW, an inversion process is used to estimate the shear wave velocity of each individual layer. The inversion process consists of the following two steps: (1) a numerical algorithm is used to estimate the representative dispersion curve and (2) an optimization algorithm is used to adjust the assumed V_s profile to minimize differences between the experimental and numerical dispersion curves. This step is similar for both SASW and MASW approaches. In this step, a dispersion curve estimated from an assumed shear wave velocity profile developed for the estimated subsurface conditions is compared with the measured representative dispersion curve. The experimental and theoretical dispersion curves are compared and adjusted via an iterative process to minimize the error or difference between the measured and estimated dispersion curves [7,8]. The least squares error method is commonly used to obtain the best fit between these two shear wave dispersion curves [9]. When there is agreement between the experimental and theoretical dispersion curves, this curve is used to estimate the shear wave velocity.

Initial Energy Source and Sensor Configuration

There are different aspects of the seismic surface wave technology being used for a variety of problems, so one of the first tasks in this research is determining which technology should adapted to investigate the complex track substructure system [10,11]. A track system is complex because of the presence of the steel rails, crossties (concrete and wood), and ballast all of which can impact the propagation and measurement of the seismic waves. In general, the distances between the sensors and the energy source control the maximum and minimum depths of investigation. Based on that general framework, the following initial locations of the seismic sensors are being used for the SASW approach, but will be refined based on initial test results. For the MASW approach, a constant sensor spacing is used at twelve or more locations and is being used herein. For both methods, a source to first receiver distance equal to the maximum depth of investigation is being used with a sensor spacing after that of 0.5 to 1.0 times the ballast thickness.

TABLE 1 – PRELIMINARY GEO-PHONE SPACING

Receiver Number	Distance from Dynamic Source	Reason for Distance
1	One-half ballast thickness	Measure V_s at shallow ballast depths to investigate ballast fouling
2	Ballast thickness	Measure V_s at base of ballast to investigate fouling
3	Twice Ballast thickness	Measure V_s in subgrade to evaluate bearing capacity and compressibility of subgrade
4	Maximum Depth of Investigation	

Implementation and Impact of Research

This research has a high likelihood of success because seismic surface wave techniques are currently being used in a wide variety of applications, including railroad applications [12], foundation engineering, ground improvement, landfill design and analysis, pavement assessment, slope stability, and bridge deck condition surveys [13,14,15,16]. It is anticipated that the resulting seismic wave technology, SASW and/or MASW, will identify problems areas in the track and in particular the initiation and rate of growth of mud spots and ballast fouling, which will improve track safety and reliability.

PROJECT OBJECTIVE AND FRAMEWORK

The main objective of this new research is to develop a land-based system for quickly and non-destructively assessing the condition of the track substructure (ballast and subgrade). It is anticipated that the resulting system will be used to provide quantitative assessment of track substructure condition, e.g., fouled ballast and weak subgrades, and engineering properties that can be used to assess track safety and reduce derailment risk. The following four main research tasks are being pursued to achieve the overall project objective above and to incorporate the system into existing FRA testing capabilities:

1. Developing Land-Based Seismic System for Track Substructure Assessment
2. Modeling Seismic Wave Techniques for Assessing Track Substructure
3. Full-Scale Testing of Land Based Seismic System at FAST High Tonnage Loop (HTL)
4. Prototype SASW System

Modeling Seismic Wave Techniques for Assessing Track Substructure

This research focuses on modeling of seismic surface waves in the railway track substructure. This modeling is being used to determine the optimal configuration of the energy source and sensors to yield the best results with depth. Wave propagation simulation software, e.g., LS-DYNA, ANSYS, and/or ABAQUS, are being used to model the track system to determine the optimal configuration of the land-based system to yield the best field results. Some of the issues that are being addressed in the modeling are: the size and location of the excitation source with different types and spacing of crossties, orientation of the geophones, e.g., perpendicular versus parallel to the rails or both, optimal spacing of the geophones to capture meaningful wave velocity profiles in a short period of time, effect of a stiff layer (ballast) over a soft layer (subgrade) in the wave propagation, etc. The presence of a stiff layer over a soft layer(s) is not expected to be a significant problem because SASW and MASW techniques are both being used successfully for pavement systems which also involve a stiff layer (pavement) over soft (subgrade) layers [9,16].

Developing Land-Based Seismic System for Track Substructure Assessment

The modeling results discussed above are being used to design and specify the necessary equipment and instrumentation for conducting surface wave measurements along railways. In particular, requirements for the wave sensors, e.g., horizontal and vertical components of the recorded motions, data acquisition equipment and software, Analog to Digital converter, computer, etc., necessary for an effective surface wave system are being developed.

Existing equipment at the University of Texas at El Paso (UTEP) is being used to test the seismic wave system to develop effective means for coupling the geophones to the ballast to measure the seismic waves. In addition, initial testing is being used to determine the optimal configuration of the system to capture meaningful shear wave velocity profiles along railroads in a short period of time. Some of the other issues being addressed in the initial experimental work are:

- size, location, and coupling of the excitation source with different types of crossties, spacing, and fastening systems,
- geophone orientation, e.g., perpendicular versus parallel to the rails or both, optimal spacing, the number of geophones for both SASW and MASW systems, and
- track time required for the measurements.

To investigate the coupling of the geophones to ballast, a large laboratory cylinder filled with representative ballast material is being used at UTEP (see Figure 3). This configuration and a hammer for the seismic source are being used to develop recommendations for size and depth of the geophone and techniques for coupling the geophone to the ballast, e.g., grout. After developing a suitable technique for coupling geophones to ballast, field testing will be performed at an abandoned freight railroad line in El Paso due to a bridge outage.

Full-Scale Testing of Land Based Seismic System at FAST High Tonnage Loop (HTL)

After the laboratory and field testing in and around UTEP, full-scale field testing of the seismic wave system will be conducted at FAST High Tonnage Loop (HTL) located at the Transportation Technology Center near Pueblo, Colorado. This site was selected for testing because the subsurface conditions have been tested and are known so the results can be used to verify the wave propagation measurement and modeling performed above. proposed to follow the TTCI study on GPR at the High Tonnage Loop (HTL) located at the Transportation Technology Center near Pueblo, Colorado. In particular, seismic wave testing will be performed at locations identified as uniform with well-defined layers by the participants of the TTCI GPR study [5] to determine how well seismic wave techniques predict the results of the sampling and testing conducted for the GPR study.

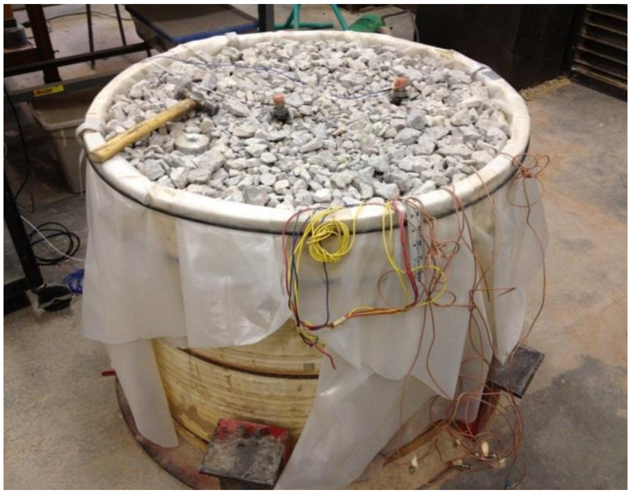

FIGURE 3 – GEOPHONE COUPLING CHAMBER AT UNIVERSITY OF TEXAS AT EL PASO

Based on the results of the full scale seismic testing at the HTL, the wave propagation modeling and equipment will be refined, if necessary, to provide a more accurate characterization of the actual track substructure conditions. Based on the testing around the HTL, additional sites for seismic testing may be sought to further validate the system.

Several new and in-service track transition locations are currently being instrumented under another FRA to measure movement with depth and to identify the layer(s) causing the observed differential movement at railroad transitions (Mishra et al., 2013). Numerical modeling of these instrumented bridge transitions need to be performed but shear strength and modulus data for the ballast and subgrade layers are needed. If feasible, the seismic wave system developed and verified at the HTL will be used at two of the instrumented bridge transition sites, e.g., Union Pacific High Speed Line in Illinois and Amtrak's Northeast Corridor near Chester, Pennsylvania, to measure shear strength and modulus profiles for use in the numerical modeling.

Prototype SASW System

After full-scale testing and validation of the surface wave system, a new SASW system that reflects the latest technology for seismic wave measurement and SASW interpretation will be developed. This system will be eventually transferred to the FRA for its use and testing of track substructures. In particular, it is planned that the SASW system can be used for quality control purposes during new construction or to assess current track condition to predict future performance and safety. The final goal is to incorporate the SASW system into the FRA's Deployable Gage Restraint Measurement System (GRMS), termed DOTX218 or T-18, which is a self-propelled rail car that uses state-of-the-art equipment to conduct performance-based testing of railroad lateral track strength. Since May 2004, the FRA has employed the T-18 to demonstrate GRMS technology, and reduce wide-gage derailments. The T-18 is the first full-sized rail car to deploy GRMS and allows measurement of rail motion under both vertical and lateral load.

SUMMARY

This paper presented the research framework and preliminary research findings of a new two-year FRA-sponsored research study aimed at developing and using seismic wave propagation principles to develop a track substructure (ballast and subgrade) condition assessment system to evaluate track safety and predict inspection intervals. This research is needed because there is no tool or system available that quantitatively measures the mechanics based properties of the layers comprising a track system. These mechanics based properties are shear modulus, modulus of deformation (Young's modulus), and shear strength and they can be derived from direct measurement of the shear wave velocity profile. Without measurement of V_s, the modulus and shear strength of the track system materials are usually estimated which leads to uncertain the numerical analyses and estimates of track safety. Finally, future project tasks involving field investigation and numerical modeling of the instrumented track transitions were outlined. Through combination of field instrumentation and numerical modeling of new and existing track transitions, this research project aims to develop design methods to mitigate the differential movement problem at such locations.

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