Measuring Railroad Ballast Modulus of Elasticity Using Light Weight Deflectometer

Emily Katherine Akey[1], Mariel W. Jones[1], Carlton L. Ho[2], and Aaron J. Rubin[1]

[1] Smith College, Picker Engineering, Northampton MA, USA
eakey@smith.edu
[2] University of Massachusetts Amherst, Civil and Environmental Engineering Department, Amherst MA, USA
ho@umass.edu

Abstract. Light Weight Deflectometers (LWDs) are used to rapidly determine the modulus of elasticity and spring constant of granular materials and pavements. The LWD can be operated by one person making it incredibly efficient to collect this important data. It is primarily used in the field to determine the properties of soils or paving materials, but also has the potential to be used on railroad ballast. However, to date, there have been minimal studies using LWDs on railroad ballast. The goal of this current study was to investigate the repeatability of LWD testing on prepared cylindrical ballast specimens. To use the LWD on ballast we conducted minimum and maximum density tests in accordance with ASTM D4254 on 12-inch interior diameter by 12-inch interior height cylinder specimens at different percentages of fouling ranging from 0 to 60% by mass. Then the LWD measurements were taken on the top of the specimen using a 12-inch diameter plate. In total, 100 measurements were made on minimum density mixtures and 50 maximum density mixtures. The effect of density and fouling on test repeatability and procedural best practices for LWD testing on cylindrical ballast specimens is discussed.

Keywords: Railroad, Ballast, Light Weight Deflectometer, Geotechnical Properties.

1 Introduction

Railroad Ballast is an essential component of many railway structures. Ballast is uniformly graded crushed stone that rests under railway ties to facilitate water drainage and support the load of trains [1]. Over time, this ballast breaks down into small fragments called fouling which fills in the void space between ballast aggregate. When all of the void space of the ballast is filled with fouling, this interferes with the function of the ballast, contributing to problems such as train derailment [1].

Inspecting ballast beds is primarily done visually without machinery or instrumentation, which allows ballast to become highly fouled before it can be seen. The material properties of fouled ballast are important for engineering evaluation of the structure-ballast-soil system. However, measuring the engineering properties of ballast is often time consuming and may require the rail service to be temporarily halted to collect in-situ measurements. The LWD is a fast and convenient non-penetrating method to collect structural properties of geotechnical materials, but its effectiveness on larger particles such as ballast is not well documented in the literature. This study focuses on the effectiveness of LWD measurements to collect modulus of elasticity data on different percentages of dry fouled ballast. The data collected was analyzed to determine the repeatability of using an LWD on fouled ballast at both maximum and minimum dry densities.

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2 Background

Estimating the elastic modulus of railroad ballast can be challenging both in the field or laboratory. Traditionally, in the laboratory, the primary method for calculating the modulus of elasticity for ballast is performing a triaxial test, which can take several days to complete and requires large molds and high capacity systems to accommodate the ballast. In this study, the possibility of using an LWD to collect modulus of elasticity data was considered. In contrast to triaxial testing, the LWD is quick and portable, allowing the same data to be collected in minutes rather than days. However, the effectiveness of the LWD on larger particles such as railroad ballast has not been well documented in the literature.

The main components of an LWD include a falling mass, load cell, and deflection plate [3]. The LWD was first invented in 1980's Germany by the Federal Highway Research Institute and HMP as an in-situ test to determine soil elasticity [4]. The typical loading plate diameter is eight inches. However, most LWD devices have detachable plates to allow other plate sizes, such as the twelve inch plate used in this study.

The entire LWD is, by name, lightweight, and able to be used by one or two people, allowing for wide uses in the geotechnical/transportation engineering fields. The LWD is primarily used to test pavements and soils in the field. One of the reasons the LWD has not been used for rougher materials in previous studies is because the plate must be level and in full contact with the sample [5]. LWD measurements are typically conducted on compacted specimens because the LWD creates an impact on the sample during testing. If the impact causes additional settlement during testing, the sample's properties have changed and thus the test may be inaccurate. The manufacturer suggests that for each LWD test, the mass is released without recording data as a settling drop to seat the plate onto the surface of the sample.

3 Methods

The procedure for using an LWD begins with raising the mass to a preset height and clicking it into place. Once the deflection plate of the LWD is resting flat against the sample, the mass is released and allowed to free-fall guided by a central rod onto the load cell attached to the deflection plate. Once the mass has rebounded, it must be caught and relocked into the handle at the top. The deflection of the plate is measured and can be used in conjunction with the force from the falling mass to estimate the spring constant (the spring constant is provided as an output by the proprietary LWD software). The modulus of elasticity within the cylinder can then be calculated from the spring constant of the sample as shown in Equation 1 [6]:

$$E = \left(1 - \frac{2v^2}{1-v}\right)\frac{4H}{\pi D^2}k \tag{1}$$

where v = Poisson's ratio (assumed v = 0.3 in this study), H = height of the mold, D = the diameter of the plate or mold, and k = spring constant as calculated by the LWD device [6].

To understand the repeatability of using an LWD on different percentages of fouled ballast, we used a 12-inch interior diameter by 12-inch interior height cylinder with dry ballast specimens prepared to different percentages of fouling ranging from 0 to 60% by mass. The test were conducted at approximately 0% water content. We conducted these tests at both minimum dry density and at maximum dry density. For each minimum density fouling percentage, we performed 20 trials, and for each maximum density fouling percentage we performed 10 trials. For both the minimum and maximum trials were split between two operators. We did not notice a significant difference between samples made by different operators. Each trial consisted of loading the cylinder with the correct mix of fouling and ballast and operating the LWD with a 12-inch plate to find modulus of elasticity. These data will be used to determine the best practices for using a LWD on ballast.

To create each sample, we air dried the ballast and fouling to near 0% water content (confirmed with oven measurements). We then mixed together fouling and ballast to either 0%, 15%, 30%, 45%, or 60% fouling. The material used was Connecticut Granite ballast prepared to AREMA #4 gradation specifications, and the same Connecticut Granite stone dust for fouling. Minimum and maximum density samples were prepared in accordance with ASTM D4254 and ASTM D4253 [2]

Fig. 1. Minimum density samples are prepared by removing a soil filled tube thus releasing the sample into the mold at an approximate minimum density.

Fig. 2. Minimum Density 60% Fouling and 40% Railroad Ballast cylinder samples. On the left is the sample after being placed into the cylinder mold, and the right is after the excess is removed to the approximate correct volume.

Fig. 3. Minimum Density 60% Fouling and 40% Railroad Ballast cylinder sample with LWD placed on top.

Typically, while using an LWD, it is suggested by the manufacturer to place the instrument on the sample and do a few "seating drops" as to establish good contact between the plate and the test material. However, with the minimum density trials, this was not possible as we did not want to change the density of the sample with the pressure from the LWD drop. During testing, it was observed that the drop weight did result in compaction of the specimen. This compaction was quantified for future analysis.

4 Results

It is generally understood that the modulus of elasticity of ballast changes according to fouling percentage and water saturation percentage. This study was interested in the functionality of the LWD at different fouling percentages that might occur. Figures 4 and 5 display the modulus of elasticity measurements for the different fouling mixes at approximately maximum and minimum density. These plots both show that there is no significant difference between the operator of different trials.

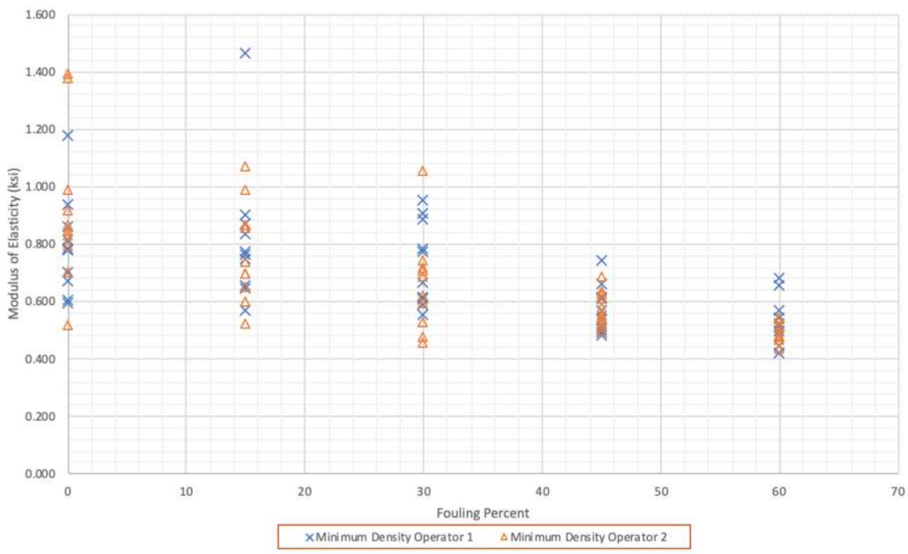

Fig. 4. Modulus of Elasticity of ballast samples at different fouling percentages for all minimum density trials conducted contrasting operators.

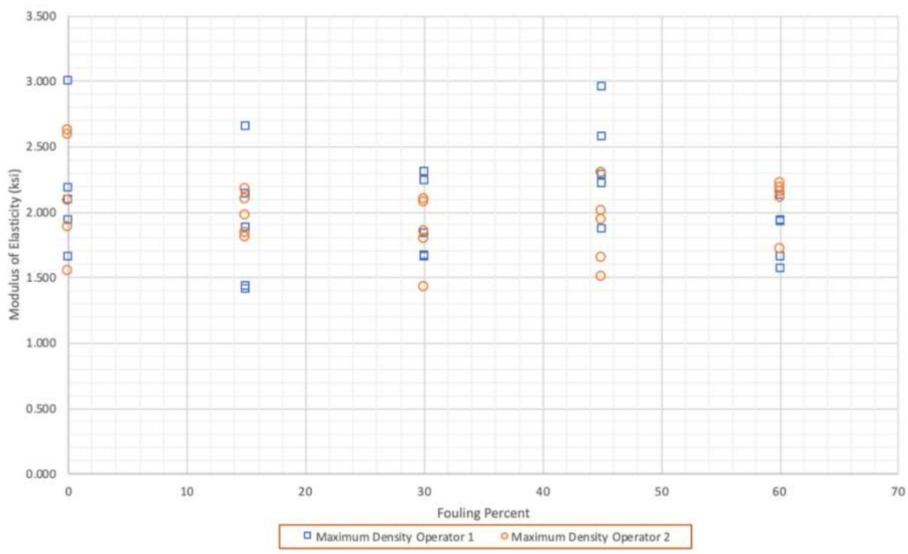

Fig. 5. Modulus of Elasticity of ballast samples at different fouling percentages for all maximum density trials conducted contrasting operators.

The table below shows the summary of average elastic modulus data taken from both relative minimum and maximum densities. As this study is one of the first to look at minimum and maximum densities of ballast, it is not certain whether the densities used are exactly minimums or maximums. However, the samples are prepared in accordance with the ASTM standards for minimum and maximum densities soil samples. In addition, the corresponding standard deviation is also calculated. This table also shows that, as expected, the maximum modulus values are higher than the minimum modulus values. For the most part, the modulus of elasticity decreases as fouling percent increases for the minimum density trials. This trend not clear for the maximum density trials. It was observed that the standard deviation values decrease as the fouling percent increases. This is expected because when the fouling percentage increases, the contact between the ballast/fouling mixture and the LWD plate also increases and therefore decreases the variability of contact pressure on the plate caused by different formations the particles (ballast and fouling) can form.

Table 1. Summary of average values for minimum and maximum densities for all trials performed on each fouling percentage along with standard deviation and acceptable range between two results.

Fouling Percent	Average E Value (ksi)	Standard Deviation (ksi)
	Minimum Density, all Trials (20)	
0	0.857	0.234
15	0.796	0.211
30	0.696	0.160
45	0.575	0.072
60	0.515	0.065
	Maximum Density, all Trials (10)	
0	2.161	0.457
15	1.942	0.363
30	1.895	0.280
45	2.131	0.433
60	1.960	0.237

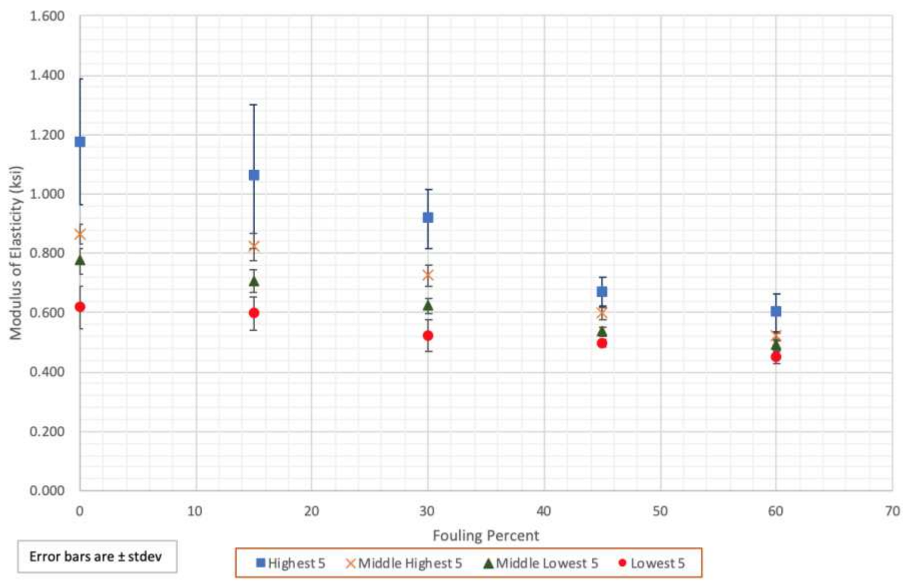

Fig. 6. Modulus of Elasticity for minimum density trials separated by averages from 5 highest, 5 highest middle, 5 lowest middle, and 5 lowest values split by fouling percentage.

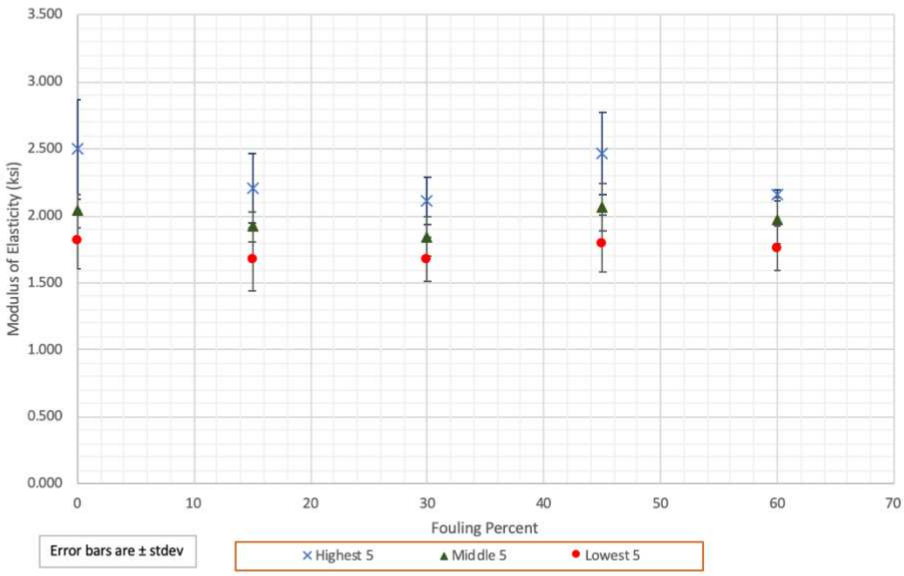

Fig. 7. Modulus of Elasticity for maximum density trials separated by averages from 5 highest, 5 middle, and 5 lowest values split by fouling percentage.

5 Discussion

To determine the repeatability of using an LWD on railroad ballast, LWD tests were performed on different mixes of ballast and fouling at both minimum and maximum dry densities. The minimum density data show a clear trend of decreasing modulus with increasing fouling. The maximum density data do not appear to show a clear trend.

For example, to see if the average modulus values from 5 trials would be significantly similar to the average modulus value for all 20 trials.

Above in Figure 6 the minimum density trials have been split into 5 tiers; highest, middle highest, middle lowest, and lowest. These correspond to the values within each fouling range. Figure 6 illustrates the spread of the minimum density data becomes smaller as we increase fouling. If the highest and lowest 5 values were removed the data would be more consistent and less variable. While there is still a small range of data for the middle values, the overall trend of modulus still decreases as fouling increases. We can also see that the highest 5 values have a much larger spread. It was observed that in this data set, that when large deviations from the mean occurred, the deviations tended to be overestimations.

Figure 7, shown below, is similar to figure 6, except with maximum density trials. The 5 highest, 5 from the middle of the data, and the 5 lowest average values are shown on this plot. The maximum data is trickier to understand. The modulus data is relatively consistent and does not have a clear negative or positive trend as fouling increases. Based on the data collected, assuming dry conditions, it does not appear that the modulus of elasticity is sensitive to the percentage of fouling present (up to 60% fouled).

In the results outlined above, it is clear that our data is fairly repeatable, but errors of +/- 25% are typical. Although, this potential error is relatively large, it can be observed that this is due to outlier data points that, individually, deviate from the mean much more than the majority of test values for a particular fouling percent. In the present study, 10 to 20 tests appear to produce a relatively reliable mean, but it is difficult with the current sample size to estimate how few trials could have been conducted while still maintaining a statistically significant mean. In future studies, this should be further investigated so that the process of estimating elastic modulus from LWD measurements can be streamlined.

In the minimum density trials, standard deviation decreases as fouling percent increases, leading us to believe that LWD data becomes more repeatable as fouling increases. The maximum data seems to be consistent as fouling increases, and the repeatability does not change as fouling increases.

Overall, using an LWD on railroad ballast to estimate modulus of elasticity appears to be feasible, but to fully quantify repeatability, more test data on dry samples as well as test data on saturated samples will need to be collected.

6 Conclusions

In this paper, LWD testing on Railroad Ballast mixed with fouling was discussed. An array of testing samples at both minimum and maximum densities and at various fouling percentages were completed in order to get an idea about how the LWD device would react with the material and to estimate whether it is feasible to use in further testing. One of the benefits of the LWD is that it can be used in the field and also on molded samples.

It is important to be mindful of the differences in support between a molded ballast sample and ballast found in real conditions under railway tracks. The lab conditions used in this study confine the ballast from lateral movement, and also vertically confine the sample from the bottom. These constrictions differ from the conditions found in reality, where ballast has minimal confinement, and the support from the bottom is less stiff than in the cast iron cylinder. Due to the containment differences between the lab conditions used in this study and in situ railroad ballast, it is anticipated that there likely are systemic differences in measured moduli between the LWD, other laboratory measured moduli such as triaxial testing, and field conditions. These differences should be researched and characterized further.

The next steps for future research on using LWD devices with railroad ballast and fouling is on saturated samples. Adding water changes strength characteristics and is an important aspect in rail bed maintenance. Knowing the effects of water on railroad ballast strength would be incredibly useful, as precipitation and bad weather are the main causes of derailment. A start to that problem is characterizing the material properties of the ballast.

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