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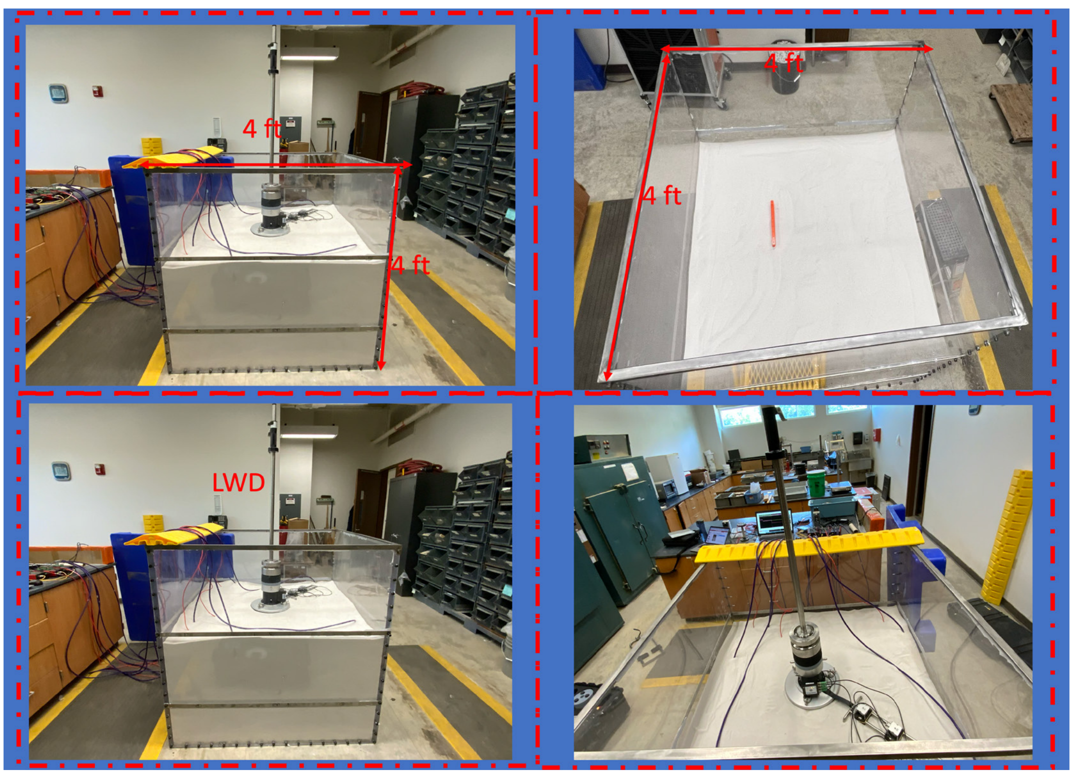
Improved Light Weight Deflectometer Test (LWD) and Analysis



Boonam Shin, Nitin Tiwari, Peter J. Becker, Antonio Bobet

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AUTHORS

Boonam Shin, PhD, PE
Research Engineer
Indiana Department of Transportation Division of Research and Development
(765) 429-9225
BShin@indot.in.gov
Corresponding Author

Nitin Tiwari, PhD
Post-Doctoral Research Assistant
Lyles School of Civil and Construction Engineering
Purdue University

Peter J. Becker, PhD, PE
Soil Foundation Research Engineer
Office of Research and Development
Indiana Department of Transportation

Antonio Bobet, Sc.D, PhD
Professor of Civil Engineering
Lyles School of Civil and Construction Engineering
Purdue University

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16. Abstract

This study focused on improving light weight deflectometer (LWD) testing protocols and understanding material and equipment variability. The Indiana Department of Transportation (INDOT) adopted the LWD test for its efficiency and effectiveness in measuring soil stiffness, a crucial parameter for pavement structural layers. However, challenges remain for implementing LWD testing, particularly in small construction areas. There are also challenges with establishing standardized performance-related criteria for various subgrade treatments. To address these obstacles, this research aimed to develop maximum allowable deflections for compaction quality assurance without relying on site-specific test sections. A large-scale laboratory testing facility was established at the INDOT research center and equipped with advanced sensing systems and a sandbox for controlled testing environments. Finite element (FE) models simulate material behavior under LWD testing conditions by using the viscoelastic plastic model to predict realistic deflection basins for different materials. Initial findings suggest that Dynatest LWD equipment provides more reliable results compared to Zorn LWD equipment, based on FE simulations. This study underscored the need for standardized calculation protocols and aimed to refine LWD testing procedures, enhancing the durability and reliability of pavement structures across various construction scenarios.

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EXECUTIVE SUMMARY

Introduction

The stability and strength of subgrade, subbase, or base courses are primarily influenced by three key factors: material type, construction methods, and environmental conditions. Among these, construction practices, compaction is often the most critical. Typically, subgrade or subbase courses are constructed using local materials such as natural or stabilized soil or granular soil. Ensuring the quality of compaction is essential, and this is commonly achieved through in-place density tests, which confirm whether the compacted soil density meets the required standards.

Currently, the sand cone test and the nuclear gauge test are the prevalent methods for measuring in-place density; however, both methods have significant drawbacks. The sand cone test, which involves digging a hole and using calibrated sand, is time-consuming and particularly challenging for granular soils. On the other hand, the nuclear gauge test, which employs a probe containing radioactive material, raises safety concerns.

Due to these disadvantages, state Departments of Transportation (DOTs) are seeking alternative methods for field soil compaction quality control. One promising alternative is the light weight deflectometer (LWD) test. The LWD test mitigates the issues associated with the sand cone and nuclear gauge tests and provides the in-situ modulus of geomaterials—a critical parameter for characterizing the properties of pavement structural layers.

LWD is an in-situ test used to assess the stiffness of constructed geomaterials by dropping a steel weight (22 lb) from a predetermined height onto a loading plate (typically 11.81 in.), resulting in a maximum average pressure of 14.5 psi on the underlying geomaterial. A built-in sensor (e.g., accelerometer) measures the resulting deflection, which is inversely proportional to the stiffness. Because it is a rapid test that yields performance-related measurements, LWD is commonly used for quality control (QC) and quality assurance (QA) in earthwork construction. For earthwork to be accepted, measured LWD deflections must not exceed a predetermined maximum deflection criterion. Maximum LWD deflection criteria have already been established for subgrade treatment types, IBC and IBL, as specified in INDOT standard specifications. As a result, maximum deflection criteria for such subgrade types must be established for each construction contract using onsite test sections (ITM 514). According to ITM 514, established maximum deflection criteria correspond to the lowest LWD deflections achieved within onsite test sections, which makes these deflections measures of site-specific index density rather than true performance measures (i.e., stiffness).

INDOT has been implementing LWD testing for compaction acceptance since the introduction of the 2016 standard specifications. LWD acceptance testing was initially limited to the compaction of aggregates; however, INDOT sought to expand LWD implementation because it was an easily operated, rapid in-situ test that assessed soil stiffness. INDOT began specifying LWD testing for chemically modified soil acceptance with the introduction of the 2018 standard specifications. However, the acceptance criteria for LWD testing of chemically modified soils was based on limited research and was not associated with performance-related engineering parameters.

Despite the advantages of the LWD test, its implementation for compaction quality assurance (QA) necessitated constructing a 100-ft-long, 24-ft-wide test section before broader application, which posed a challenge in small construction areas like bridge approaches, lane widening, patching, and shoulders where the use of aggregate No. 53 was common and constructing a test section was impractical. With over 200 LWD devices currently employed in INDOT construction projects, maintaining a robust quality control process demands timely and accurate calibration and verification of these devices. This research study was conducted to address these challenges, specifically to develop maximum allowable deflections for compaction QA.

INDOT required a procedure for establishing maximum LWD deflection criteria for chemically or non-chemically modified subgrades that preserves the performance-related qualities of LWD and does not rely on constructing site-specific test sections. The solution to INDOT's dilemma was to establish a specialized laboratory testing program; however, no such full-scale laboratory LWD equipment existed. Therefore, the goal of this study was to develop a robust large-scale laboratory testing facility at the INDOT research center to facilitate the quality control testing of materials for contractors and develop acceptable deflection criteria for different materials used in pavement. This testing facility can also be used to better understand material behavior and deflection basin mapping using advanced sensing systems to develop testing protocols that can give better correlation with falling weight deflectometer (FWD) or laboratory-based testing, such as resilient modulus.

Since Indiana contractors use Zorn and Dynatest LWD equipment frequently, it was also necessary to calculate equipment-related factors for developing a standardized calculation protocol. This study expanded to include the use of finite element (FE) models to simulate different materials and test conditions. These FE models were compared with large-scale laboratory and full-scale accelerated pavement testing (APT) based physical models.

Findings

Based on the initial experimental and numerical analysis, the following observations were made.

- The integration of the viscoelastic plastic model into LWD measurements heralded a notable advancement in geotechnical investigation of subgrades. This enabled more accurate and reliable predictions of pavement and soil behavior under impulsive loading conditions. The viscoelastic plastic model's detailed consideration of the hysteresis effect—observed during impulsive loading using LWD—provided a tangible representation of material responses over time. This led to a richer comprehension of the dynamic behavior of pavements and soils.
- The close alignment between results derived from proposed finite element method (FEM) simulations and laboratory scale physical and full scale APT experimental testing underscored the accuracy and applicability of the viscoelastic plastic model. This further affirmed its potency in capturing the material's time-sensitive response.
- The laboratory scale experimental setup was equipped with sensors and was well-calibrated with static and dynamic loadings. This facility was capable of testing controlled sections with varying material and environmental conditions and therefore can be used to develop reliable deflections criteria.
- Initial results suggested that Dynatest LWD equipment provided more reliable results than the Zorn LWD equipment. This finding was based on FE simulations; therefore, laboratory testing was required to make well-informed decisions.

Implementation

The successful implementation of improved LWD testing methods for soil compaction quality control involved a multifaceted approach that included developing a state-of-the-art laboratory testing facility, establishing standardized testing protocols, integrating advanced finite element (FE) modeling, and ensuring rigorous calibration and verification of LWD equipment. The following are the current benefits the facility provides and ways it can be of further use in the future.

Laboratory Testing Facility Development

This large-scale laboratory testing facility was equipped to perform LWD tests, thus providing opportunities to test different materials under controlled conditions. The current facility includes a sandbox, which can accommodate different degrees of compaction and saturation, and type of material, thus allowing for precise and consistent testing environments. INDOT will be able to enhance its quality control process by using this facility.

Standardized Testing Protocols

Standardized testing protocols were developed to ensure consistency and reliability in LWD measurements. These protocols included detailed procedures for conducting LWD tests, calibrating equipment, and interpreting results. They also specify the conditions under which tests should be conducted, such as the type of loading plate and the drop height, ensuring that LWD tests provide accurate and comparable results across different construction sites and projects.

Finite Element (FE) Modeling and Numerical Simulations

Finite element (FE) models that simulate the behavior of various materials under LWD testing conditions were developed using the viscoelastic plastic material model. These simulations predicted deflection basins for modified, stabilized, and natural materials. The FE models were validated through comparisons with laboratory and full-scale experimental tests. Thus, the models can provide realistic deflection basins, which can be used for Mechanistic-Empirical Design (MEPDG) purposes.

Calibration and Verification

The laboratory facility may serve as a central hub for the calibration and verification of LWD equipment, which is crucial given the widespread use of these devices in INDOT construction projects. The calibration process will involve regular checks of the devices' performance against known standards and adjustments, as necessary, to ensure accuracy. By implementing a rigorous calibration and verification process, INDOT can maintain the reliability of LWD measurements across all projects.

Equipment-Specific Protocols

Since Indiana contractors primarily use Zorn and Dynatest LWD equipment, equipment-specific protocols have been developed. These protocols account for the unique characteristics and performance of each type of equipment, ensuring that deflection criteria are applicable regardless of the LWD device used. The study's initial findings suggested that Dynatest equipment provided more reliable results; however, further laboratory testing is necessary to confirm these findings and refine the protocols.

Training and Education

Training programs should be developed for INDOT personnel and contractors to support the successful implementation of LWD testing. These programs should cover the standardized testing protocols, equipment calibration and verification procedures, and interpretation of LWD test results. By providing comprehensive training, INDOT can ensure that all stakeholders are equipped with the knowledge and skills necessary to conduct LWD tests accurately and effectively.

The implementation of LWD testing should be an ongoing process, with continuous monitoring and improvement based on field data and feedback from users. Regular reviews of the deflection criteria and testing protocols should be conducted to ensure that they remain relevant and effective. Additionally, advancements in LWD technology and testing methodologies should be incorporated into the process, ensuring that INDOT maintains a state-of-the-art approach to soil compaction quality assurance.

The successful implementation of this research study will enhance the quality control and assurance processes for INDOT construction projects. By developing robust acceptance criteria, establishing a specialized laboratory facility, and creating standardized testing protocols, INDOT will be better equipped to ensure the durability and reliability of pavement structures across various construction scenarios.

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1. INTRODUCTION

1.1 Overview

The stability and strength of subgrade, subbase, or base courses are primarily influenced by three key factors: material type, construction methods, and environmental conditions. Among these, construction practices—particularly compaction—are often the most critical. Typically, subgrade or subbase courses are constructed using local materials such as natural or stabilized soil or granular soil. Ensuring the quality of compaction is essential, and this is commonly achieved through in-place density tests, which confirm whether the compacted soil density meets the required standards.

Currently, the sand cone and the nuclear gauge tests are the prevalent methods for measuring in-place density. However, both methods have significant drawbacks. The sand cone test, which involves digging a hole and using calibrated sand, is time-consuming and particularly challenging for granular soils. On the other hand, the nuclear gauge test, which employs a probe containing radioactive material, raises safety concerns.

Due to these disadvantages, state Departments of Transportation (DOTs) are seeking alternative methods for field soil compaction quality control. One promising alternative is the light weight deflectometer (LWD) test. The LWD test mitigates the issues associated with the sand cone and nuclear gauge tests and provides the in-situ modulus of geomaterials—a critical parameter for characterizing the properties of pavement structural layers.

The Indiana Department of Transportation (INDOT) has been incrementally implementing LWD for QA testing since the introduction of the 2016 standard specifications, initially for various subgrade treatments and aggregate bases. LWD is an in-situ test used to assess the stiffness of constructed geomaterials. The test involves dropping a steel weight (22 lb typically) from a predetermined height onto a loading plate (11.81 in. typically), resulting in a maximum average pressure of 14.5 psi on the underlying geomaterial. A built-in sensor (e.g., accelerometer) measures the resulting deflection, which is inversely proportional to stiffness. Because it is a rapid test yielding performance-related measurements, LWD is commonly used for quality control (QC) and quality assurance (QA) in earthwork construction. For earthwork to be accepted, measured LWD deflections must not exceed a predetermined maximum deflection criterion. Maximum LWD deflection criteria have already been established for subgrade treatment types of IBC and IBL, as specified in INDOT standard specifications. As a result, maximum deflection criteria for such subgrade types must be established for each construction contract using onsite test sections (ITM 514). According to ITM 514, the maximum deflection criteria correspond to the lowest LWD deflections achieved within onsite test sections, making these deflections measures a site-specific index rather than true performance measures (i.e., stiffness).

INDOT has been implementing LWD testing for compaction acceptance since the introduction of the 2016 standard specifications. LWD acceptance testing was initially limited to the compaction of aggregates; however, INDOT has sought to expand LWD implementation because it is an easily operated, rapid in-situ test that assesses soil stiffness. INDOT began specifying LWD testing for chemically modified soil acceptance with the introduction of the 2018 standard specifications. However, acceptance criteria for LWD testing of chemically modified soils were based on limited research and were not associated with performance-related engineering parameters.

Despite the advantages of the LWD test, its implementation for compaction quality assurance (QA) necessitates constructing a 100-ft-long, 24-ft-wide test section before broader application, which poses challenges in small construction areas such as bridge approaches, lane widening, patching, and shoulders where the use of aggregate No. 53 is common and constructing a test section is impractical. With over 200 LWD devices currently employed in Indiana Department of Transportation (INDOT) construction projects, maintaining a robust quality control process demands timely and accurate calibration and verification of these devices. This research study was conducted to address these challenges, specifically to develop maximum allowable deflections for compaction QA.

INDOT requires a procedure for establishing maximum LWD deflection criteria for chemically or non-chemically modified subgrades that preserves the performance-related qualities of LWD and does not rely on constructing site-specific test sections. The solution to INDOT's dilemma could involve implementing a specialized laboratory testing program; however, no such full-scale laboratory LWD equipment currently exists. Therefore, the goal of this study is to develop a robust large-scale laboratory testing facility at the INDOT research center to facilitate the quality control testing of materials for contractors and develop acceptable deflection criteria for different materials used in pavement. This facility can be used to better understand material behavior and deflection basin mapping using advanced sensing systems, to develop testing protocols that can give accurate correlations with the falling weight deflectometer (FWD) or laboratory-based testing such as resilient modulus.

Since Indiana contractors majorly use Zorn and Dynatest LWD equipment, it is also necessary to calculate the equipment-related factors to develop a standardized calculation protocol. This study also includes the use of FE models to simulate different materials and test conditions. These FE models are compared with large-scale laboratory and full-scale accelerated pavement testing (APT) based physical models. The successful implementation of this research study will enhance the quality control and assurance processes for INDOT construction projects. By developing robust acceptance criteria, establishing a specialized laboratory facility, and creating standardized testing protocols, INDOT will be better equipped to ensure the durability and reliability of pavement structures across various construction scenarios.

1.2 Background and Problem Statement

In recent years, the subgrade's role in the pavement structure has garnered significant attention from scholars and practitioners alike. With resilient modulus being a primary material property of the subgrade, its accurate determination is crucial for pavement design and performance evaluation (Ng et al., 2017; Rahman & Gassman, 2019). Non-destructive testing instruments, such as the falling weight deflectometer (FWD), have become indispensable tools for pavement assessment (Göktepe et al., 2006; Hoffman & Thompson, 1982; Xu et al., 2002). To meet the demand for efficient and rapid soil foundation testing, the lightweight deflectometer (LWD) (see Figure 1.1) emerged as a practical alternative to the conventional FWD. Both instruments operate on similar principles, but the LWD's portability and reduced weight make it highly suitable for onsite applications (Grasmick et al., 2015; Stamp & Mooney, 2013). Weingart pioneered the development and evaluation of LWD in 1977, laying the foundation for its widespread adoption in geotechnical engineering.

Whether employing FWD or LWD, the objective remains the same—applying an impact load on the subgrade surface using a free-falling weight (Foinquinos et al., 1995). Subsequently, load and displacement responses are recorded, facilitating back analysis to determine the subgrade's modulus (Senseney et al., 2013). This approach provides valuable insights into the subgrade's behavior, aiding in pavement design and construction decision-making processes. Over the past few decades, researchers have explored efficient methods to evaluate mechanical properties of soils and pavement materials. The LWD has emerged as a promising tool to assess the elastic modulus of soils through a direct and straightforward approach. Its non-destructive nature and ease of use have led to its increasing popularity in geotechnical engineering and pavement construction.

Despite the LWD's limitations compared to the trailer-mounted falling weight deflectometer (FWD), such as its limited load range (typically around 10 kN), it remains suitable for assessing soils and granular materials commonly used in pavement layered systems, especially in moderately stiff surface layers like asphalt concrete (Horak, 2008; Nazzal, 2003). Its portability, lighter weight, and ease of transportation enable onsite testing and efficient field compaction quality control, making it a valuable tool in pavement construction and rehabilitation projects (Fleming, 2007; Nazzal, 2003). The LWD's capability to apply stress impulses that simulate loading conditions experienced in pavements allows for quick and efficient assessment of the elastic properties of pavement layers and subgrade. By providing representative measurements without the need for intrusive testing, the LWD reduces construction time, costs, and environmental impacts. Its widespread adoption has been observed in various states and transportation departments for pavement performance evaluation and quality assurance (Davich et al., 2006; Mooney & Miller, 2009; Siekmeier et al., 2009; Volovski et al., 2014).

As the importance of reliable determination of mechanical properties in pavement design and construction intensifies, the LWD's popularity is expected to grow further. Researchers and practitioners should focus on refining testing methodologies, enhancing measurement accuracy, and establishing standardized

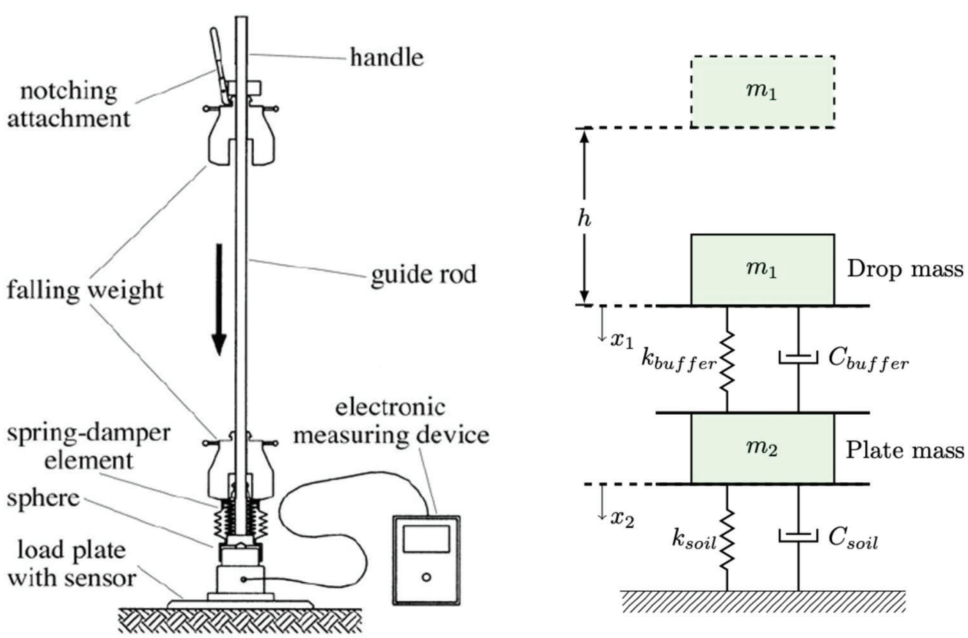

Figure 1.1 Schematic of light weight deflectometer (LWD).

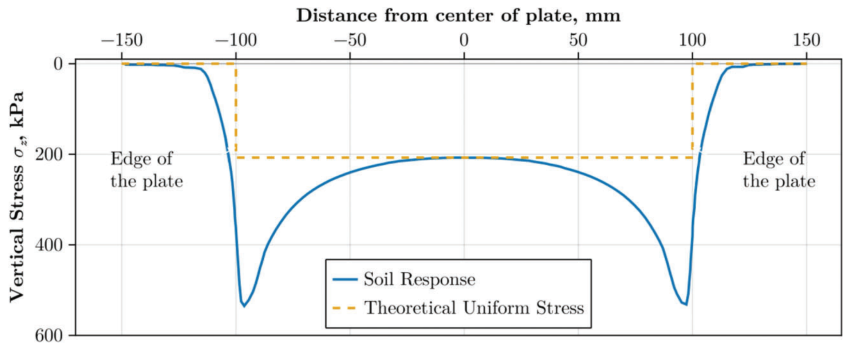

Figure 1.2 Theoretical and experimental soil response under LWD loading.

procedures to fully leverage the potential of LWD in geotechnical engineering endeavors.

Back calculation is a common method employed with LWD to determine the material properties of pavement layers based on their response to surface loading (Mehta & Roque, 2003). This inverse analysis involves estimating the elastic modulus of each layer from the measured deflection response. Traditionally, the back calculation method relies on linear elastic theories, which may lead to inaccuracies due to simplifications in the pavement's real behavior (Asli et al., 2012) (see Figure 1.2). To improve the accuracy of back calculation with LWD, finite element modeling (FEM) can be utilized. FEM is a powerful numerical analysis technique that can simulate the actual behavior of pavements under load, accounting for nonlinear effects and complex material properties (Hu et al., 2019).

By incorporating FEM modeling into the back calculation process, it becomes possible to consider the actual stress and strain distributions within the pavement layers, providing more realistic and accurate estimates of their elastic properties. FEM modeling allows for the inclusion of various parameters, such as pavement layer thickness, material properties, and boundary conditions, resulting in a more comprehensive assessment of the pavement's response to LWD loading. Furthermore, FEM modeling enables the investigation of different loading scenarios and subgrade conditions, providing valuable insights into pavement behavior under varying conditions. This enhanced understanding can lead to improved pavement design and maintenance strategies, optimizing the performance and longevity of pavement structures (Wang & Al-Qadi, 2013). To ensure the accuracy and reliability of the finite element modeling (FEM) in simulating LWD testing, a comprehensive large-scale physical model experiment is essential. This experiment aims to replicate real field conditions while offering controlled laboratory conditions, facilitating systematic investigations and allowing direct comparison between the physical and numerical responses.

One of the goals of this study is the development of a robust numerical model that accurately simulates the impulsive loading generated by the LWD during testing, considering variations in drop heights and weights. The model's validity is confirmed by comparing its predictions with a large-scale physical model test setup, which replicates real field conditions, ensuring precise estimation of LWD-induced deflections. Employing a laboratory physical model allows for better control over soil behavior, which is often challenging to achieve in the field. This controlled environment facilitates systematic investigations and the formulation of standard testing protocols. Analysis of different loading configurations helps optimize LWD testing protocols and promote standardization. By refining the numerical model's accuracy through controlled testing and validating against the physical model, the study aims to improve LWD loading simulations and subsequently enhance assessments of soil subgrade properties. Furthermore, the laboratory setup enables exploration of diverse soil conditions and LWD testing scenarios, contributing to the establishment of best practices and standardized procedures for geotechnical projects. Ultimately, the research aspires to advance non-destructive testing techniques, deepen our understanding of soil subgrade behavior, and provide practical tools to optimize pavement design and construction processes

1.3 Scope of Project

This project aims to establish a specialized testing program for the determination of maximum LWD deflection criteria in lieu of field test sections. A prototype laboratory lightweight deflectometer (LLWD) test setup designed and constructed as part of this project (Phase 1) can act as the focal point for the specialized testing program. Analysis procedures for processing raw test results into meaningful properties (e.g., in situ LWD deflection, resilient modulus, etc.) could then be developed based on the findings of multiple experiments with the prototype LLWD (Phase 2).

2. DEVELOPMENT OF LAB SCALE LABORATORY TESTING FACILITY

To advance geotechnical testing, the Indian Department of Transportation (INDOT) has established a large-scale laboratory physical model. This state-of-the-art facility has been purposefully assembled to conduct physical model testing, allowing for an in-depth exploration of soil behavior.

2.1 Testing Facility

The laboratory physical model is shown in Figure 2.1. A key consideration in designing this facility is the selection of an appropriately sized model to mitigate the impact of boundary conditions. By opting for a 4 ft × 4 ft × 4 ft size, aim to minimize boundary effects, thereby ensuring accurate and reliable test results. The implementation of this large-scale laboratory physical model marks a significant step forward in geotechnical testing, providing valuable insights into failure mechanisms and soil behavior. The facility's capacity to visualize deflection basins during load applications enhances our comprehension of soil responses, facilitating the development of more robust and efficient geotechnical solutions for future infrastructure projects.

2.2 Design of Testing Box

The testing box, constructed from acrylic material, measures 4 ft × 4 ft × 4 ft (Figure 2.2). It is designed to facilitate advanced visualization techniques to assess the actual deflection basin and its progression over time. This design anticipates the future use of Particle Image Velocimetry (PIV) with soft computing to analyze the deflection profiles of various materials. Additionally, high-speed cameras and 3D pressure distribution sensors, utilizing advanced fiber optics, may be employed to comprehensively study material behavior.

Figure 2.3 illustrates the empty sandbox located at the INDOT West Lafayette research facility. The sandbox is also designed to accommodate future research involving static or cyclic actuators. Its dimensions and thickness, with additional structural support at 1/3 and 2/3 of its height, ensure a rigid boundary condition. This robust design is crucial for obtaining accurate and reliable testing results.

Finite element models were utilized to determine the necessary boundary conditions for LWD testing. A rigid plate with a diameter of 0.3 meters (1 ft) and a cubic box with equal dimensions was analyzed using FEM. The simulations were conducted using one-fourth of the volume, leveraging symmetry to optimize computational efficiency. The model featured fixed lateral and bottom boundaries, and a constant pressure of 100 kPa was applied to the top of the rigid plate (Figure 2.3).

The minimum recommended box dimension is 1.2 m × 1.2 m × 1.2 m (4 ft × 4 ft × 4 ft) to minimize errors in horizontal stresses and settlements (Table 2.1), noting that vertical stresses are insensitive to box dimensions. It is important to consider that the fixed boundary conditions represent an extreme scenario, as frictional boundaries would be more compliant and result in smaller errors.

2.3 Loading System

This research explores building a laboratory-scale light weight deflectometer (LLWD) to minimize human errors during the lifting of the falling weight in the LWD test. The idea was to use an electromagnetic force

Figure 2.1 Physical model testing setup (INDOT facility).

Figure 2.2 Testing sand box.

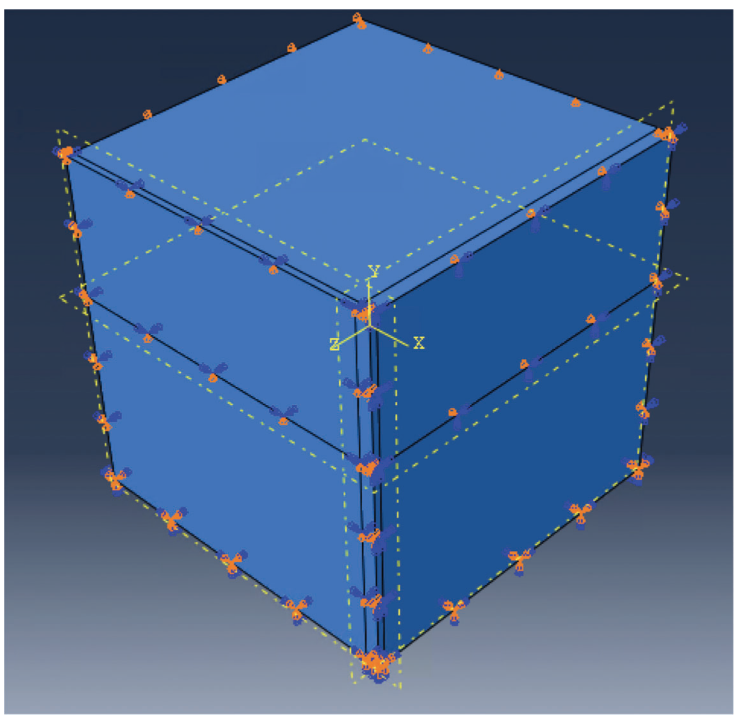

Figure 2.3 FE simulation of sand box.

to automatically lift the weight. This loading arrangement was designed considering the same principle used for the soil compactor (Figure 2.4). Considering the complexity of fabrication and potential delays to the project, the plan could be explored in future research projects.

To apply the loading for the light weight deflectometer Zorn ZFG 3000 (Figure 2.5), and Dynatest LWD 3032 (Figure 2.6). Two different LWDs has been considered to understand the equipment variability in testing. A detailed comparison of both equipment is shown in Table 2.2.

The LWD's versatility allows it to test thin asphaltic pavements, foamed bitumen-bound recycled materials, unbound subbase, and subgrade. The obtained LWD measurements yield valuable insights into the strength

TABLE 2.1
Dimensions of sand box with error percentage

Width (m)	d (mm)	d/d_3	Error (%)
3	0.32	1.00	–
2.4	0.32	0.99	1.25
1.8	0.31	0.96	3.75
1.5	0.30	0.94	5.94
1.2	0.29	0.91	9.38
0.9	0.27	0.85	15.00
0.6	0.24	0.73	26.56

of multiple pavements layers. The LWD complies with ASTM 2583 standard for determining material modulus and compaction. Its exceptional quality and portability facilitate easy measurements, even in remote locations. Moreover, the Dynatest LWD allows for the use of different weight options to suit specific applications. Researchers can choose from 10 kg (traditional), 15 kg, and 20 kg weights based on the project's requirements (Figure 2.7). This flexibility ensures precise and tailored testing, optimizing the accuracy and relevance of the obtained results.

2.4 Instrumentation

2.4.1 Data Acquisition System

The data acquisition (DAQ) system used for experimental testing is the STS4-4-TE4 model (Figure 2.8). This system is designed to handle various measurement types, including analog input and temperature input, ensuring comprehensive data collection for the testing protocols. It supports both analog single-ended or differential inputs and 3KΩ NTC thermistor temperature inputs, with a maximum sample rate for analog input of 1,000 samples per second (S/s) and a fixed sample rate for temperature input of approximately 1 S/s. The system offers 11 programmable gain settings, allowing for precise adjustment and optimization of input signals, and features a 24-bit Sigma-Delta ADC for high-resolution conversion of analog signals to digital format.

The DAQ system is equipped with 4 input channels, accommodating various sensor inputs, and has 4 dedicated thermistor inputs for temperature measurements. It supports RS232/422/485 serial communication, ensuring versatile connectivity options. Additionally, it includes isolated digital inputs (up to 24V) and 2 digital outputs, enhancing its control capabilities. The system provides a +15 Vdc output at 200 mA, suitable for powering external sensors.

The DAQ system offers programmable excitation voltages (Vx) of +0 to +5 Vdc at 20 mA per channel and a combined V+15 output of +15 Vdc at 400 mA. It operates on a +24 Vdc supply at 1.0 Amp, ensuring robust power delivery, and supports +24 Vdc Passive Power over Ethernet (PoE) at 0.5 Amp, facilitating flexible installation and power options. The system includes 10T-Base (TCP/IP) Ethernet connectivity, allowing for reliable network communication. The STS4-4-TE4 DAQ system's advanced capabilities and robust design make it an ideal choice for detailed and accurate data collection in experimental testing environments. Its combination of high-resolution measurement capabilities, versatile input and output options, robust data storage, and flexible power and communication features ensures comprehensive and reliable performance, enhancing the quality and efficiency of the experimental testing process.

2.4.2 Soil Compression Sensors

Soil compression sensors (SCS) are employed to measure vertical displacements in unbound materials (Figure 2.9). These sensors are particularly suitable for use in pavements, highways, runways, and railways, and are integrated into various construction materials, including base, subbase, subgrade, grade,

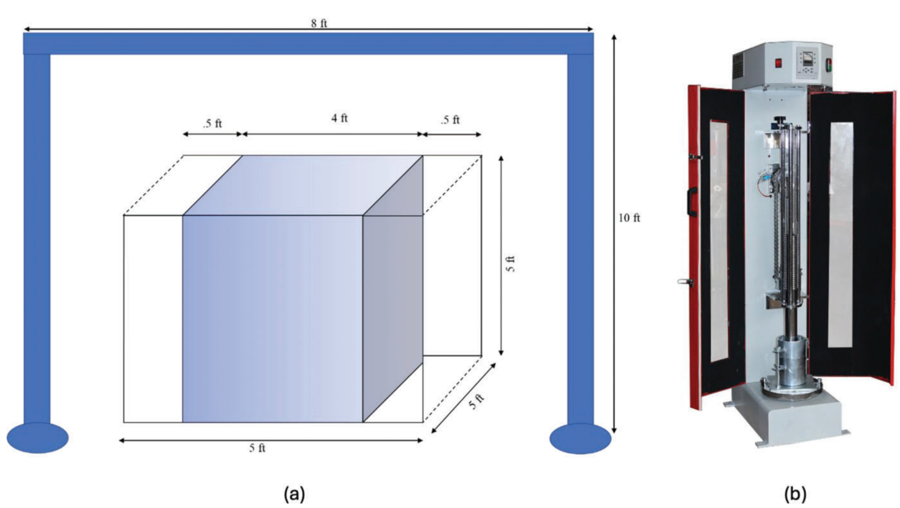

Figure 2.4 (a) Proposed experimental setup, and (b) loading arrangement.

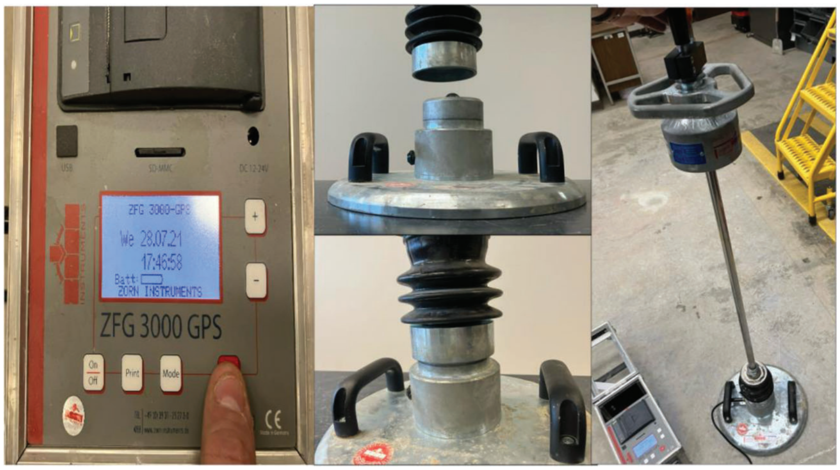

Figure 2.5 Zorn LWD (ZFG 3000).

Figure 2.6 Dynatest (LWD 3032).

TABLE 2.2
Comparison between Zorn and Dynatest LWD

Feature	Zorn ZFG 3000	Dynatest LWD 3032
Manufacturer	Zorn Instruments	Dynatest
Weight	~10 kg	10 kg standard 5 kg, 15 kg, 20 kg optional
Load	10–15 kN	Up to 15 kN
Plate Diameter	300 mm	Dual plate system 300 mm and 150 mm
Display	Digital display with data logging	Digital display with advanced data logging and analysis
Data Transfer	USB port	Bluetooth connectivity
GPS	Not available	Built-in GPS
Software	Basic software for data logging	Advanced software for comprehensive data analysis. Mobile app
Interface	User-friendly	Advanced with graphical output
Real-time Data Display	Yes	Yes
Robust Construction	Yes	Yes
Additional Features	Simple and durable	GPS tracking, wireless data transfer

and ballast layers. The SCS sensors are highly effective for measuring the dynamic response of soil layers, such as real-time deflections caused by LWD impulsive load. SCS sensors are specifically designed to measure the compaction or expansion of soils in various subsurface layers. Utilizing displacement transducers, these sensors can measure a maximum length of 10 in.

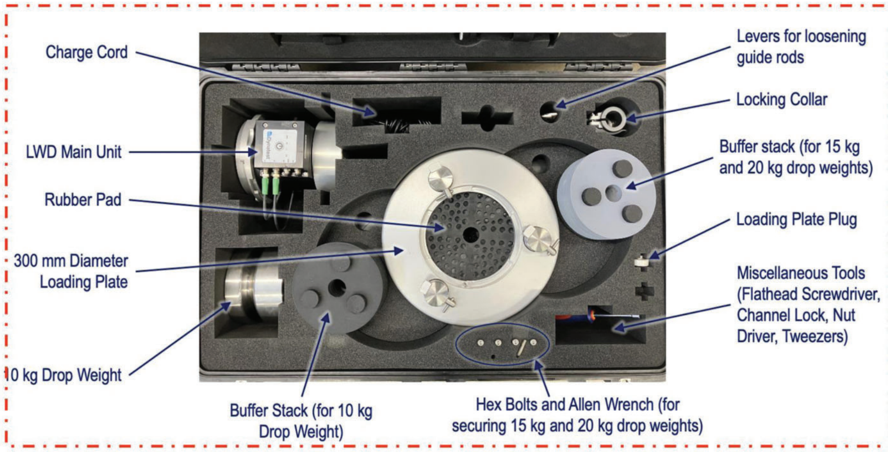

Figure 2.7 Dynatest LWD testing equipment.

Figure 2.8 STS-4 DAQ.

2.4.3 Earth Pressure Cell

Earth pressure cells (EPC) are used to measure the vertical pressure exerted on soil layers (Figure 2.10). The EPCs used in this study have a standard range of 1 MPa with a high resolution of 0.025% and can withstand up to 1.5 times the rated pressure. These sensors are designed to operate within a temperature range of -20°C to +80°C, making them suitable for a wide variety of environmental conditions. The physical dimensions of the EPCs are 6 mm in height and 230 mm in diameter.

2.4.4 Fiber Bragg Gratings (FBG) Sensor

Soil compression sensors, SCS, only provide measurements at discrete points. The potential for continuous monitoring using Fiber Bragg Grating, FBG, sensors was explored. The sm125 Fiber Optic Sensing Interrogator by Luna Innovations (micron optics) was employed to achieve precise and reliable measurements. The device was configured with eight parallel channels and a sampling rate of 2 Hz. It supports a wavelength range of 1,500–1,600 or 1,460–1,620 nm, with a wavelength accuracy and stability of 1 pm, and a repeatability of 1 pm, 0.05 pm at 1 Hz. The interrogator offers a dynamic range of 25 dB peak and 40 dB full scale, with full spectrum measurements included at a data rate of 10 Hz. The optical connectors are of type LC/APC. The interrogator is compatible with various sensors, including Fiber Bragg Gratings, Long Period Gratings, Fabry-Perot, and Mach-Zehnder Interferometers. Its physical dimensions are 117 mm × 234 mm × 135 mm; and has a weight of 2 kg, with operating conditions ranging from 0°C to 50°C and storage conditions from -20°C to 70°C. The input voltage is 9-36 VDC, with an AC/DC converter included, and the power consumption at 12 V is typically 20 W, with a maximum of 30 W. With high-performance on-board Digital Signal Processing (DSP) and real-time Field-Programmable Gate Array (FPGA) processing, the sm125 enables rapid data acquisition and flexible peak detection algorithms, proving to be an essential tool for fiber optic sensing in various challenging applications worldwide.

FBG sensors were calibrated well with strain gauge sensors used for measuring soil deflections and proved

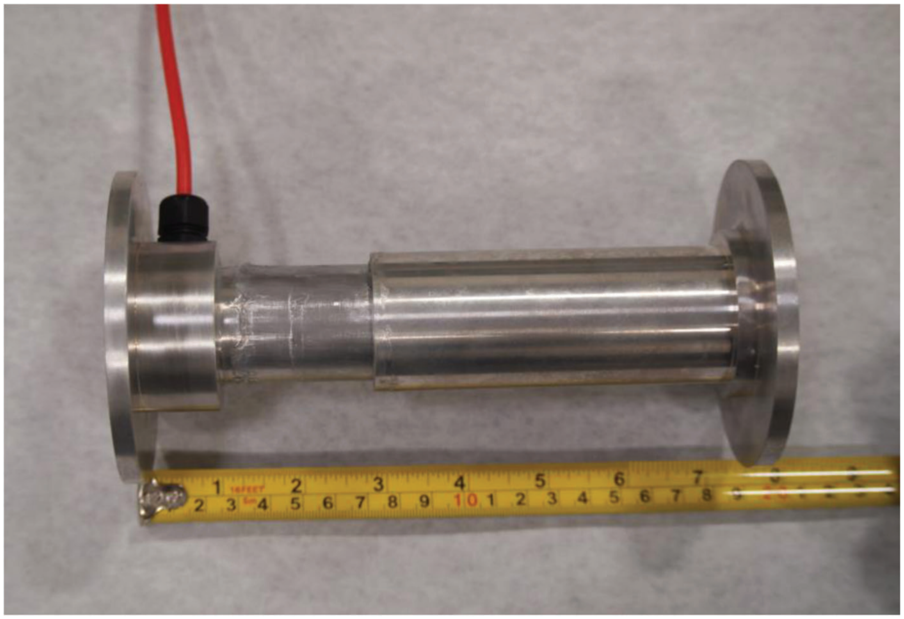

Figure 2.9 Soil compression sensor (SCS).

Figure 2.10 Earth pressure cell (EPC).

to be effective for the continuous monitoring of the deflection basin (Figure 2.11). However, FBG sensors are temperature -sensitive, indicating the need for further research. This research proposes employing FBG sensors due to their high sensitivity and potential to create a 3D array of sensors. This array can map the 3D deflection profile of the soil, thereby enhancing the understanding of the material's behavior.

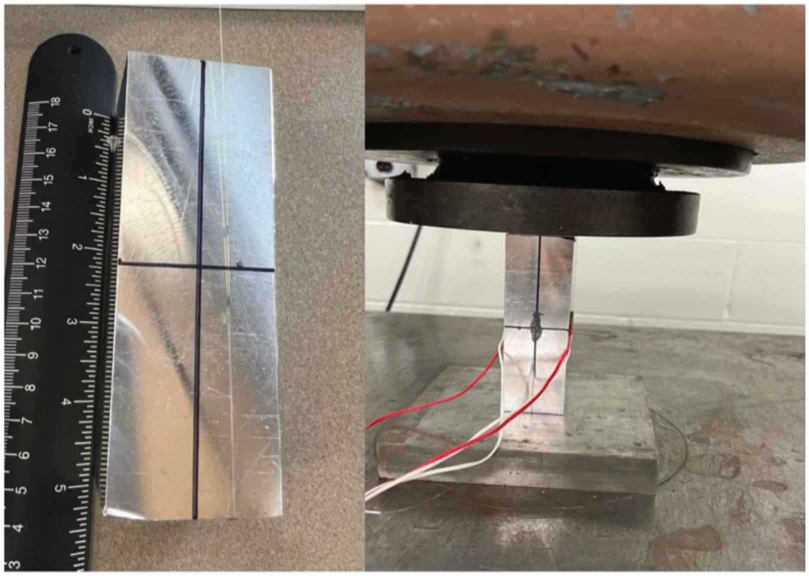

Figure 2.11 Calibration of FBG sensor with strain gauge.

3. BACK-CALCULATION OF ELASTIC MODULUS FOR LWD

LWD stiffness back calculation assumes a loading of 1,590 lb applied uniformly over a circular area, resulting in a surface deflection predicted from classical Boussinesq stress distribution. Because this method does not consider the complex nuances of the LWD, the results are no more than stiffness index values that do not directly translate to design engineering properties (e.g., resilient modulus). The conventional back calculation approach neglects the utilization of time-history curves and fails to account for the nonlinearity and displacement hysteresis of subgrades exhibiting visco-elastic-plastic behavior. Both theoretical research and laboratory tests have indicated a strong viscoelastic plastic behavior of subgrades, leading to an over-estimation of their stiffness. Such overestimation significantly impacts the service life of the pavement structure (Fan et al., 2022; Zhang et al., 2020). As a result, it becomes imperative to identify a more effective method for back-calculation of the modulus of subgrades.

3.1 Mechanical Forward Model

The mechanical calculation model used in this research is depicted in Figure 3.1. The study explores the viscoelastic-plastic behavior of soils, particularly within the framework of the MOSWL (Modified Single Whisker Loop) model (Lai et al., 2016). It aims to derive a general solution algorithm for a layered viscoelastic system based on the Lamé's equation and obtain an explicit displacement solution in a viscoelastic semi-infinite space under arbitrary axisymmetric loading conditions, while incorporating the actual boundary conditions.

It is important to note that in viscoelastic-plastic materials, a hysteresis phenomenon frequently occurs (Yu et al., 2020). This phenomenon is analogous to the displacement hysteresis observed in roadbeds under impact loads, and previous studies have revealed that soil exhibits more complex viscoelastic plastic behavior (Wang et al., 2023; Zhang et al., 2023). To accurately describe the subgrade's mechanical behavior, selecting an appropriate viscoelastic plastic model is crucial (Wang et al., 2023).

Commonly used elastic and viscoelastic models include the Hook's model, Maxwell model, and the Kelvin model, and their combinations. The Maxwell model consists of springs in series with dampers, while the Kelvin model employs parallel connections between springs and dampers. Both models can capture the hysteresis phenomenon under external loads, but only the Maxwell model can adequately describe transient

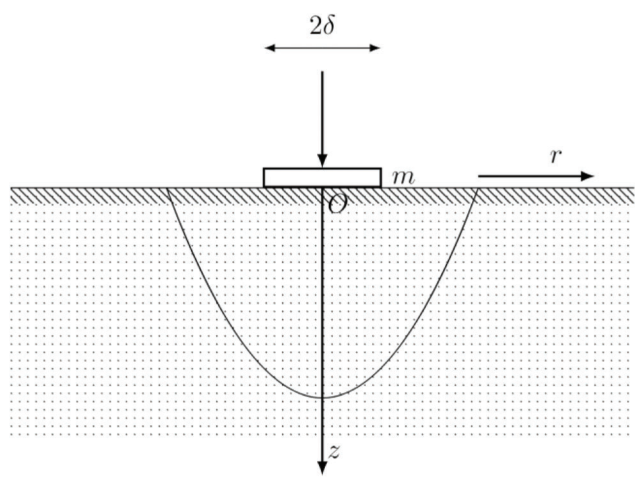

Figure 3.1 Mechanical calculation model.

elasticity and nonlinear relaxation phenomena, making it more suitable for modeling the behavior of the subgrade (Lai et al., 2016). For tests such as the LWD, the viscoelastic-plastic seems appropriate because it can account for the repeated impact of a hammer that eliminates plastic deformation at the measuring point. Its ability to capture this real-world behavior makes it an ideal choice for such scenarios. Moreover, the viscoelastic-plastic model strikes a balance between accuracy and simplicity, making it computationally efficient and easy to interpret. This efficiency allows researchers and engineers to gain deeper insights into the subgrade's response to external forces, providing valuable information for optimizing subgrade materials in engineering projects (Yu et al., 2020). Considering all the factors mentioned, this study adopts a viscoelastic plastic model, which consists of a spring and Maxwell model connected in series. To enhance the viscoelastic model proposed by Zhang et al. (2020), the Newtonian dashpot is replaced with the Abel dashpot (see Figure 3.2).

The mechanical behavior of the subgrade is described using the Nishihara model, which incorporates the viscoelastic-plastic nature. This model combines elements of viscoelasticity and plasticity to account for the time-dependent and rate-dependent responses of materials under loading (see Figure 3.3).

The Nishihara model defines the viscoelastic response using the concept of a Prony series, which is a sum of exponential terms. The Prony series is used to represent the relaxation behavior of viscoelastic materials. Additionally, the model includes a plasticity component to describe the plastic deformation of the material when subjected to high stresses.

The basic conditions for the Nishihara model are as follow.

$$\begin{aligned} &\sigma = \sigma_1 = \sigma_2 = \sigma_3 \\ &\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \\ &\sigma_1 = E_1 \varepsilon_1 \\ &\sigma_2 = E_2 \varepsilon_2 + \eta_1 \dot{\varepsilon}_2 \\ &(\sigma_3 - \sigma_{s1} = \eta_2 \dot{\varepsilon}_3) \end{aligned} \quad \text{(Eq. 3.1)}$$

Taking the Laplace transform of Equation 3.2 we obtain.

$$\tilde{\varepsilon} = \frac{\sigma}{E_1 s} + \frac{\sigma}{S(E_2 + \eta_1 s)} + \frac{\sigma - \sigma_{s1}}{\eta_2 s^2} \quad \text{(Eq. 3.2)}$$

Taking the Laplace inverse transform of Equation 3.3 we obtain the creep formula as follows.

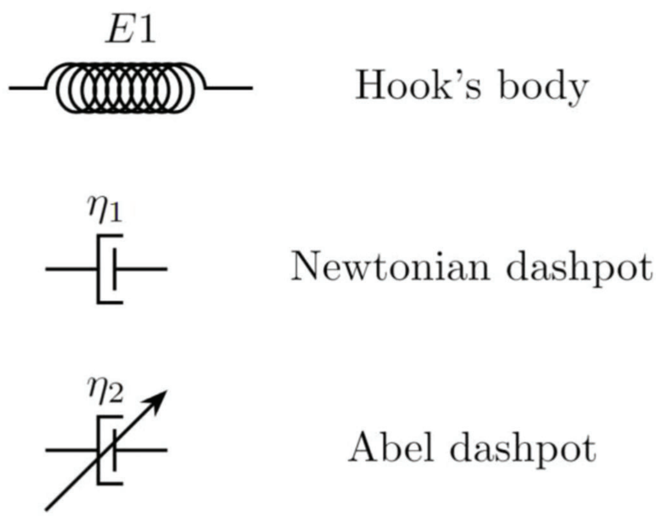

Figure 3.2 Basic model elements.

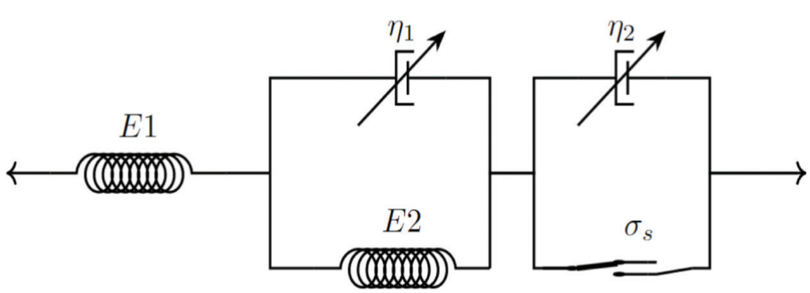

Figure 3.3 Nishihara viscoelastic-plastic model.

$$\varepsilon = \frac{\sigma}{E_1} + \frac{\sigma}{E_2}\left(1 - e^{-\frac{E_2}{\eta_1}t}\right) + \frac{\sigma - \sigma_{s1}}{\eta_2}t \qquad \text{(Eq. 3.3)}$$

The Nishihara model, the viscoelastic plastic operator E(s) can be expressed as:

$$E(s) = \frac{E_1(s\eta_1 + E_2)(s\eta_2 + Q(s))}{(s\eta_1 + E_2)(s\eta_2 + Q(s)) + E_1(s\eta_2 + Q(s)) + E_1(s\eta_1 + E_2)} \qquad \text{(Eq. 3.4)}$$

Where,

$$Q(s) = \frac{(E_1 + E_2)\eta_1 s + E_1 E_2}{E_1 + s\eta_1} \qquad \text{(Eq. 3.5)}$$

Various load distribution types have been explored by researchers, including uniform load, bowl-shaped load, and parabolic load (Gerrard & Wardle, 1980). Building upon these traditional load forms, Gerrard and Wardle (1980) introduced the general form of an arbitrary vertical axisymmetric load.

$$p(r,t) = \begin{cases} mp(t)\left(1 - \frac{r^2}{\delta^2}\right)^{m-1} & r \le \delta \\ 0 & r > \delta \end{cases} \qquad \text{(Eq. 3.6)}$$

where $p(r, t)$ = the expression of load distribution; m = the load type coefficient (m = 0.5, 1, and 1.5 for rigid, uniform, and bowl-shaped stresses distribution, as shown in Figure 3.4; δ = the radius of the loading plate; $p(t)$ = the evenly distributed load concentration; and r = the distance from the calculation point to the center of the load.

Asli et al. (2012) utilized parabolic loads to model the interaction between the roadbed and the rigid loading plate. In elastic theory, the load distribution under the rigid plate is commonly represented as parabolic (Figure 3.4). Consequently, the parameter "m" was assigned a value of 0.5 in Equation 3.2. To accommodate arbitrary time-history curves, Boltzmann's viscoelastic linear superposition principle was incorporated in this study, and the arbitrary load function "$p(t)$" was discretized based on this principle as:

$$p(t) = H(t)p_0 + \sum_{i=1}^{n-1} H(t - \tau_i)\Delta p_i \qquad \text{(Eq. 3.7)}$$

where n = the total number of discrete segments; $H(\cdot)$ = the step function; p_0 = the initial load value; Δp_i = the load change value on each stage, $\Delta p_i = p_i - p_{i-1}$; τ_i = the starting moment of the i-th stage. See Figure 3.5.

From Equations 3.6 and 3.7, using m = 0.5, the discrete series expansion for a parabolic, axisymmetric load can be obtained as

$$p(r,t) = \begin{cases} p_a(r,t)p_0 + \sum_{i=1}^{n-1} p_a(r,\, t - \tau_i)\Delta p_i & r \le \delta \\ 0 & r > \delta \end{cases} \qquad \text{(Eq. 3.8)}$$

where $p_a(r,t) = 0.5H(t)[1 - (r/\delta)^2]^{-0.5}$.

If the subgrade displacement response at the center of the surface, known as the standard displacement response function $f(t)$, can be calculated under the applied load $p_a(t)$, then the displacement response under any load can be obtained based on this function.

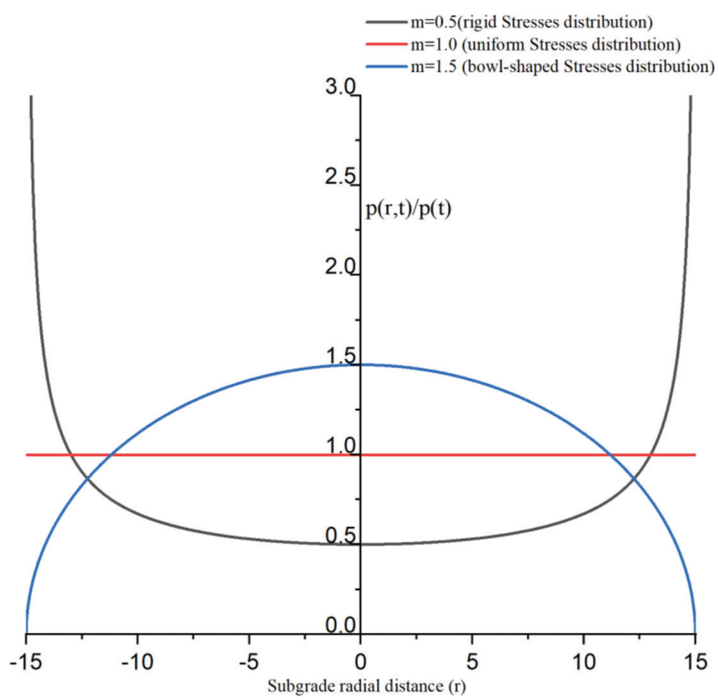

Figure 3.4 Relative load distribution curves for different values of m.

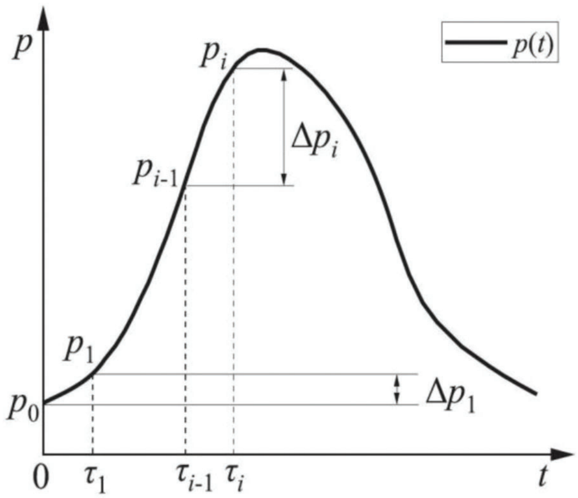

Figure 3.5 Schematic diagram of $p(t)$.

$$\omega(t_i) = f(t_i)p_0 + \sum_{i=1}^{n-1} f(t_i - \tau_i)H(t_i - \tau_i)\Delta p_i \quad \text{(Eq. 3.9)}$$

where $\omega(t_i)$ = the displacement response at the load center and at time t_i. In a cylindrical coordinate system, the Lamé equations under Laplace transformation can be obtained from Equation 3.7, when $r = 0$, $z = 0$, the function $f(t)$ can be obtained as follows:

$$f(t) = \frac{\delta(1-\mu^2)\pi}{2} \left[\frac{1}{E_2} - \frac{E_1}{E_2(E_1+E_2)} e^{((-E_1E_2)/(E_1+E_2)\eta)t}\right] \quad \text{(Eq. 3.10)}$$

Take t → 0 and t → + ∞, respectively. Equation 3.10 yields

$$\begin{cases} f(0) = \lim\limits_{t=0} f(t) = \dfrac{\pi}{4} \times \dfrac{2\delta(1-\mu^2)}{E_1+E_2} \\ f(\infty) = \lim\limits_{t\to+\infty} f(t) = \dfrac{\pi}{4} \times \dfrac{2\delta(1-\mu^2)}{E_2} \end{cases} \quad \text{(Eq. 3.11)}$$

According to Equation 3.10, the expression of elastic modulus is:

$$\begin{cases} E_{t=0} = \dfrac{\pi}{4} \times \dfrac{2p\delta(1-\mu^2)}{pf(0)} = E_1 + E_2 \\ E_{t\to\infty} = \dfrac{\pi}{4} \times \dfrac{2p\delta(1-\mu^2)}{pf(\infty)} = E_2 \end{cases} \quad \text{(Eq. 3.12)}$$

Equation 3.12 is the solution of the elastic half space based on the Boussinesq's theory, which proves the correctness of Equation 3.10. In addition, the subgrade has an instantaneous elasticity at the initial moment of $E_1 + E_2$, and that it will gradually decrease over time and finally reach a stable value of E_2.

4. FINITE ELEMENT MODEL DEVELOPMENT

In this study, an axisymmetric model (Figure 4.1) was utilized for the simulations using the FE general-purpose software ABAQUS, to analyze the subgrade deflections under the impact load of the LWD.

To leverage the problem's symmetry and save computational resources, only a quarter of the cube model was used (Tarefder & Ahmed, 2014). To minimize the influence of boundary conditions on the simulation results, the domain was carefully chosen to be larger than 12–20 times the radius of the loading area in the horizontal direction and larger than 50 times in the vertical direction.

The impact load from the LWD was simulated by adding an initial velocity to the drop weight. LWD load is applied using a spring-mass system. In this setup, two plates of the same mass relate to a spring and placed on the soil surface. The falling weight is simulated using an additional rigid body, which is released to fall on the loading plate based on the required velocity to impact the hammer on the loading plate (Figure 4.1). The velocity is calculated for different weights and heights of the falling weight, allowing for flexible loading conditions during the simulation.

The numerical modeling approach began with the creation of several FE models with varying subgrade properties, including stiffness and viscosity. These models were subjected to the simulated impact loads from LWD. Time-history responses, particularly deflection, were computed for each model under these different loading conditions. The LWD simulations employed a calculation time of 20 ms and an incremental step of 0.2 ms. Additionally, the falling height of the drop hammer was set at 90 cm, and the speed for the LWD was 4.2 m/s.

To obtain accurate material properties for the subgrade, modulus back-calculation was performed using the obtained time-history deflection data, and subsequent investigations considered the influence of the subgrade model size by analyzing four groups of FE models with different dimensions. A mesh convergence study determined a stable and computationally efficient size for the subgrade model, set at 1.2 × 1.2 m. Table 4.1 presents the material parameters and element properties used in the simulations.

Simulating the contact between the subgrade and the loading plate in the LWD setup involved adopting a lateral non-sliding and normal hard contact setting. The axisymmetric FE model utilized a nonuniform structured meshing technique to achieve computational efficiency while accurately representing the subgrade's complex behavior (Figure 4.2). This approach featured finer and more refined meshing under the loading plate region, ensuring precise capture of the dynamic response in areas of interest. The mesh size increased as the distance from the loading plate increased, optimizing computational effort while maintaining resolution (Kim et al., 2009). The nonuniform structured meshing strategy was carefully chosen to minimize the

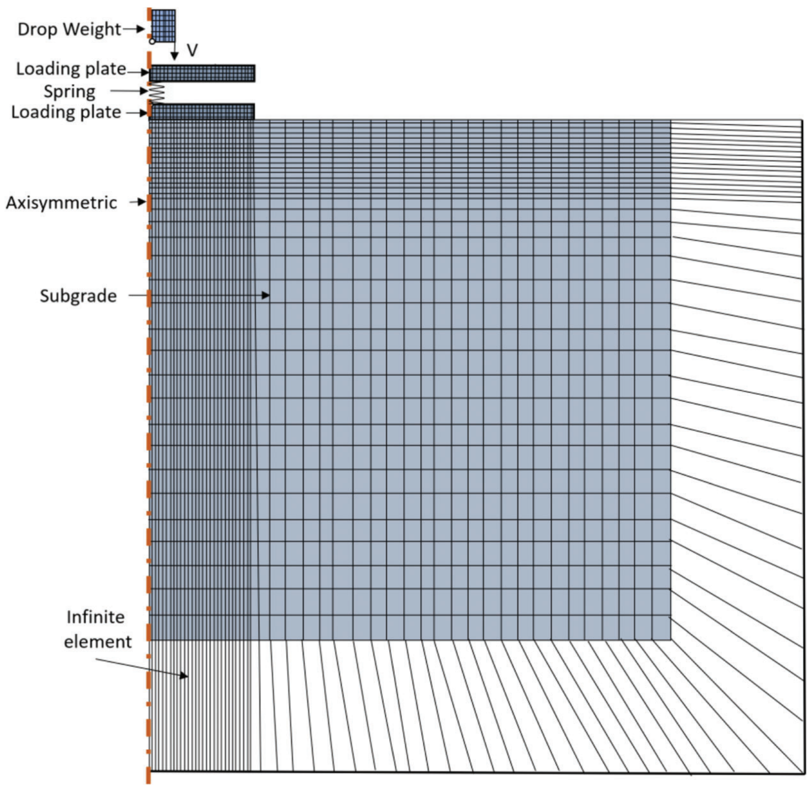

Figure 4.1 FEM model with boundary conditions and loading system.

TABLE 4.1
FE model parameters and mesh properties

Name	Element Type	Materials Properties	Moduli (MPa)	Poisson's Ratio	Density (kg/m^3)
Drop Weight	CAX4	Elastic	2.1×10^5	0.25	7.5×10^3
Loading Plate	CAX4	Elastic	2.1×10^5	0.25	7.5×10^3
Subgrade	CAX4	Elastic	30, 40, 50, 60	0.35	2.0×10^3
–	CINAX4	Viscoelastic	–	–	–
Spring	Spring	–	Spring stiffness coefficient: 5.6×10^5 kN/m		

computation time without sacrificing the overall accuracy of the simulation.

An axisymmetric FE model with infinite elements at the boundary was constructed to further enhance computational efficiency while maintaining accuracy (Wang & Al-Qadi, 2013). Boundary effects were addressed by treating the outer boundary of the subgrade in the axisymmetric FE model as an infinite element. Based on a mesh convergence study conducted by Al-Qadi et al. (2008), the infinite boundary must be > 1.2 m from the load center in three directions to obtain stable solutions. This approach effectively minimized the influence of boundary conditions, providing more accurate simulations by replicating actual conditions where the subgrade extends infinitely beyond the finite model boundaries. For the subgrade, eight-node solid elements were employed, and infinite elements were positioned at the boundaries to eliminate the effects of wave reflection during the dynamic analysis.

The subgrade was modeled as a generalized Maxwell solid using the Prony series in the ABAQUS software. The relaxation modulus equation described its behavior, and material parameters for the viscoelastic plastic model proposed equation (Eq. 3.10) were determined through calibration using experimental data.

$$G_R(t) = G_0\left[1 - \sum_{i=1}^{N} g_i^{-p}\left(1 - e^{-t/\tau_i^G}\right)\right] \quad \text{(Eq. 4.1)}$$

For N = 1 in the previous equation, the specific Prony series is obtained as

$$G_R(t) = \frac{1}{2(1+\mu)}\left[E_1 + E_2 - E_1\left(1 - e^{-\left(E_1 t/2(1+\mu)\eta\right)}\right)\right] \quad \text{(Eq. 4.2)}$$

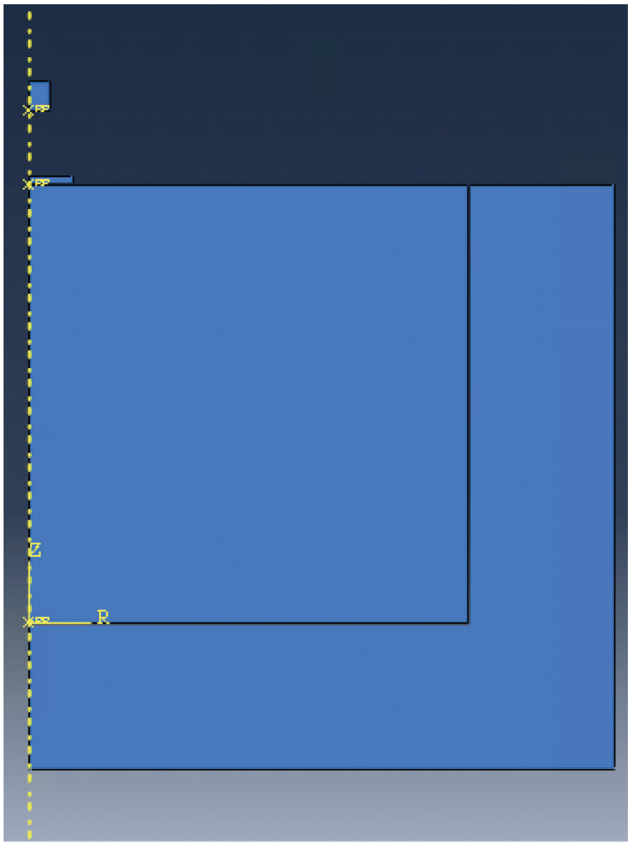

Figure 4.2 FE model Abaqus CAE.

Where N, G$_0$, g_i^{-p}, τ_i^G are the material parameter with the viscoelastic model (Zhang et al., 2020b).

The time-history curve was generated by analyzing displacement and force data at the center point of the loading plate. The dynamic response of the subgrade was assessed for various subgrade sizes, verifying the accuracy and efficiency of the modeling method under LWD loading conditions. The results of the finite element simulation were compared to the experimental results, including deflections (obtained from SCS) and applied load (obtained using EPS) from physical model testing, to validate the accuracy of the simulations. The numerical modeling approach detailed in this section provides a step-by-step account of the procedures used to develop and analyze the FE models, taking into consideration the specific loading conditions of the simulated LWD impact loads. This approach offers reliable insights into the time-history response of the subgrade under the impact loading conditions of the test.

5. VERIFCATION OF FE MODEL USING LARGE-SCALE LABORATORY PHYSICAL MODEL

5.1 Experimental Program

The testing box was filled with Wedron uniform silica sand up to a depth of 2 ft, creating a representative soil subgrade within the model. This depth was chosen based on FE simulations to avoid the rigid bottom boundary effect. The sand utilized in the testing, commercially known as 430 Wedron Uniform Silica Sand, closely resembled the Standard Ottawa Sand's gradation curve (Figure 5.1). Extensive laboratory tests were conducted to determine essential properties, including the maximum and minimum void ratios and the internal friction angle (derived from direct shear tests) for the 430 Wedron Sand. The results revealed that the maximum void ratio was 0.770, while the minimum void ratio was 0.496. Additionally, the internal friction angle ranged from 31° to 37°, corresponding to relative densities between 20% and 80%, respectively, with effective stresses (σ') spanning from 30 to 125 kPa. To calibrate the sand's compaction effort, a method involving the number of drops from a specific weight and height was employed. By compacting the sand in three layers, each layer subjected to a 4 lb weight dropped from a height of 4 in., a relative density of approximately 33% was achieved.

The Dynatest and Zorn light weight deflectometers were employed to apply impulsive loading and evaluate soil behavior. These portable versions of the falling weight deflectometer (FWD) utilizes a load cell and geophones, ensuring accuracy comparable to the traditional FWD.

Five earth pressure cells and three soil compression sensors were placed at a 10-cm depth from the top of the testing box. The configuration of the sensors and the physical model are depicted in Figure 5.2. To measure the deflection under the maximum applied load, an EPC and SCS were placed at the center of the loading plate. Additionally, two SCS sensors were placed at distances of 30 cm and 40 cm to observe the formation of the deflection basin. EPC cells were distributed in different directions, as shown in Figure 5.2, at distances of 25 cm, 30 cm, 40 cm, and 50 cm from the center of the loading plate. These varying distances were selected to observe the radial load distribution.

5.2 FE Simulation Results

Figure 5.3 shows the results obtained from the axisymmetric FE model, depicting the stress and displacement-time-history curve at the loading center (30 MPa, 10 kPa · s). The load-time-history curve represents the impact force on the loading plate. Notably, there is a time difference of approximately 3 ms between the peaks of the two curves.

5.3 Comparison Between FE Simulation and Laboratory Results

Figure 5.4 is a comparison between the results obtained from the finite element method (FEM) simulations and the experiments. Notably, the responses of the FEM and the applied load closely align, exhibiting a remarkable concurrence between the two. The error is less than 1%, indicating an acceptable

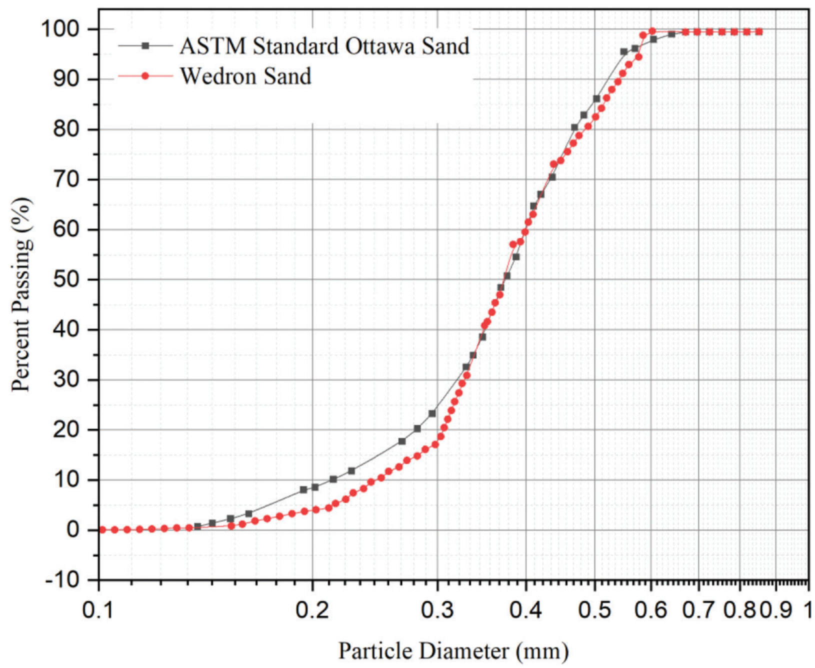

Figure 5.1 Grain size distribution of ASTM Ottawa sand and Wedron sand.

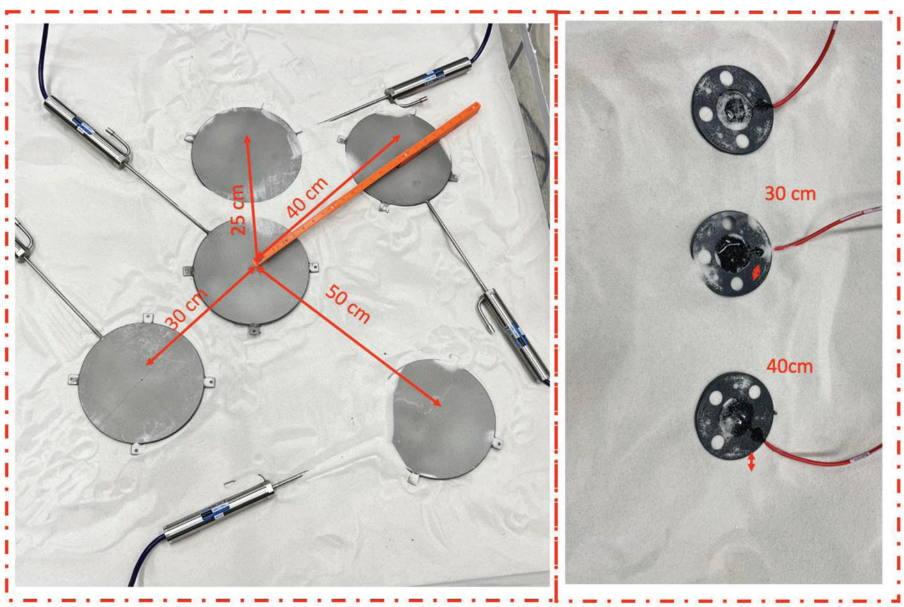

Figure 5.2 Earth pressure cell and soil compression sensors configuration.

agreement between the FE model with viscoelastic plastic properties and the results from experimental testing. This close agreement between the FEM and experimental results reinforces the accuracy and reliability of the viscoelastic plastic model in capturing the dynamic behavior of pavements and soils under varying loading conditions.

During the impulsive loading using the LWD, the hysteresis effect becomes evident due to the viscoelastic nature of the pavement or soil materials. When the LWD applies rapid and repeated impulses to the surface, the material undergoes dynamic deformation, resulting in a time-dependent response. In numerical simulations using the viscoelastic plastic model, the hysteresis effect is incorporated to account for the material's viscoelastic properties. The model considers the viscosity and energy dissipation characteristics, leading to a delayed and non-reversible deformation behavior during impulsive loading. The stress-strain curves obtained from FEM simulations for viscoelastic materials exhibit loops or hysteresis loops, indicating the accumulation of deformation over successive

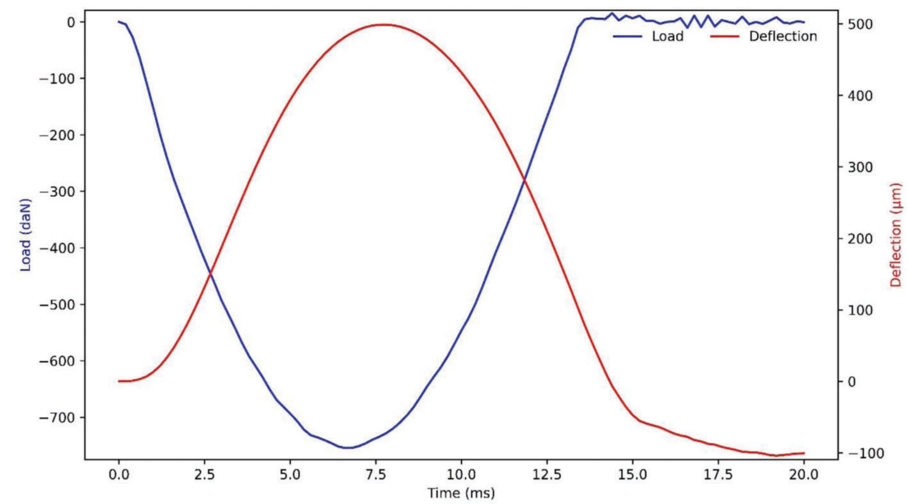

Figure 5.3 LWD loading and corresponding deflection from FE model (30 MPa, 10 kPa · s).

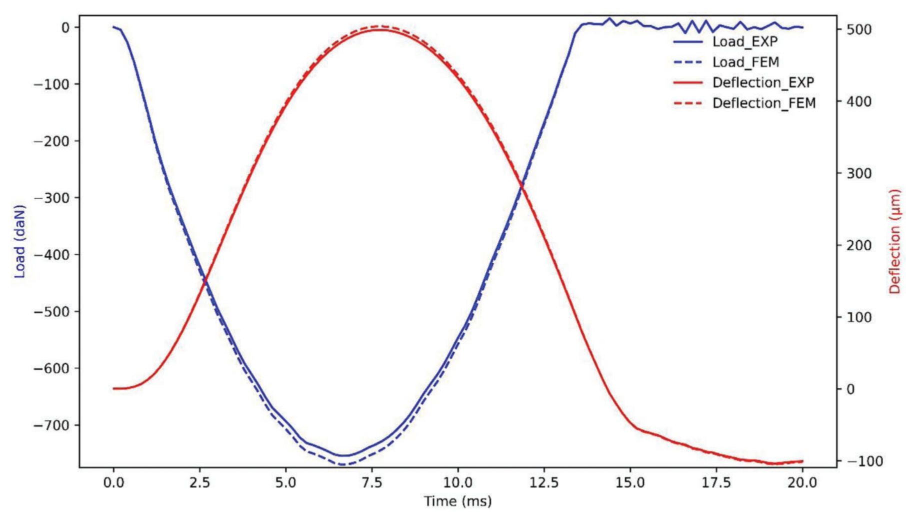

Figure 5.4 Compression of FE model and physical model results.

impulses. In experimental testing with LWD, the hysteresis effect is observed when the surface is subjected to repetitive impulses. The material responds with a lag in deformation, demonstrating energy dissipation and changes in its stress-strain behavior. As each impulse is applied and removed, the material may not fully recover its original state, leading to non-reversible deformations.

Recognizing and accounting for the hysteresis effect during impulsive loading applied using LWD is crucial for accurately assessing the dynamic behavior of pavements and soils. By understanding the material's time-dependent response, engineers can make informed decisions regarding the pavement's resilience and long-term performance under repetitive traffic loads or cyclic loading conditions. The incorporation of the viscoelastic plastic model in numerical simulations allows for a more comprehensive analysis of the hysteresis effect and facilitates the design of more reliable and durable transportation infrastructure.

6. VERIFCATION OF FE MODEL USING FULL-SCALE ACCELERATED PAVEMENT TESTING

6.1 APT Facility

Accelerated pavement testing, APT, techniques provide an opportunity to investigate pavement behavior in cost- and time-efficient ways, whereby the amount of damage that might take more than 10 or even 20 years to occur in the field can be achieved in a matter of months. During the past several decades, there has been an increased interest in APTs. APT facilities and methods such as circular tracks, linear tracks, and mobile loading machines, have been developed worldwide. APTs have been used extensively in areas such as (1) the development and validation of pavement analysis and design models; (2) research into pavement mechanics and damage mechanisms; (3) identification of deficiencies in current practices; (4) development of performance-based specifications or tests for asphalt concrete pavements; (5) investigations into correlations between laboratory experiments and real long-term pavement performance; (6) efficiency and impact of implementing innovative materials, designs, specifications, construction standards, vehicle technology, rehabilitation techniques, etc.; (7) evaluation of load damage equivalency and the remaining life of pavements; and (8) improved vehicle–pavement interaction, including advanced load and contact stress models.

The Indiana Department of Transportation's Accelerated Pavement Testing Facility is located at the INDOT's Research and Development site in West Lafayette. The APT site consists of a pit 20 ft (6.10 m) in width and length and 6 ft (1.83 m) deep. The APT loading is performed by a heavy vehicle prototype consisting of a set of wheels with full-scale tires mounted to a large steel frame carriage, as shown in Figure 6.1. The loading is applied using a set of pneumatic cylinders that provide steady force during the APT trafficking. For this study, the loading applied was 20,000 lb (9.07 ton) using a conventional dual tire set-up with a tire pressure of 100 psi (0.69 MPa). The continued APT loading mimics many years of in-service pavement loading in just a few months.

The INDOT APT heavy vehicle also includes an automated laser system mounted behind the wheel assembly. The laser system can be used to measure longitudinal and transversal pavement profiles over time. The facility is equipped with a radiant heating system and ground heating lamps, as shown in Figure 6.1, to maintain elevated air and pavement temperatures. The APT loading machine can apply both unidirectional and bi-directional trafficking. Only unidirectional movement was used during this study. The APT control room is equipped with two computers and a control panel. One computer is used for APT control and programming, and the other is used for data acquisition

The use of the APT sections can reduce the required number of field roadway segments, as the APT sections led to lower standard errors due to well-controlled test conditions and measurement procedures. The paving materials used in this APT study were designed to replicate a previous APT study by Nantung et al. (Nantung, Lee, & Tian, 2018). Both surface mixes (HMA and SMA) have a performance grade of 70-22 and NMAS 9.5, a conventional mix PG used for surface courses in Indiana. The intermediate and base mixes have similar characteristics except for the binder; the performance grades are 64-22 and 76-22 PG, respectively. Aggregate gradation charts along with corresponding control points were specified using the INDOT standard. It should be noted that intermediate and base courses consisted of the same aggregate gradation. In this report, only information on the subgrade preparation is included.

6.2 Pavement Cross Section

Four different thin, flexible full-depth pavement sections were designed and constructed following conventional INDOT full-depth flexible pavement specifications. As shown in Figure 6.2, Lanes 1 and 2 have an overall asphalt thickness of 10 in. Both lanes are identical except that Lane 1 has a 1.5-in. dense-graded hot mix asphalt (HMA) surface layer, and Lane 2 has a 1.5-in. stone matrix asphalt (SMA) surface layer.

Both lanes have a 2.5-in. intermediate asphalt course and a 6-in. asphalt base course. Lanes 3 and 4 have an overall pavement thickness of 7 in. and are identical except for the surface course. While Lane 3 has a SMA surface course, Lane 4 has a dense-graded HMA

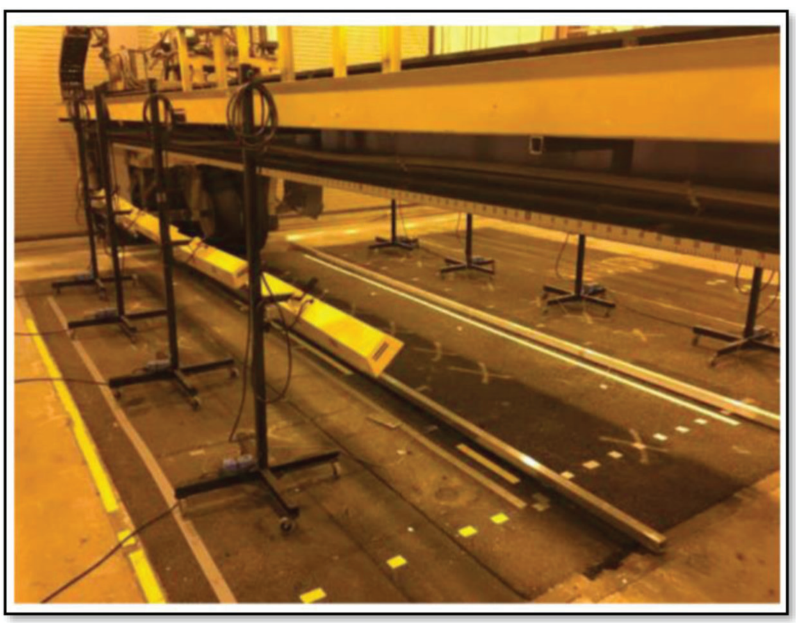

Figure 6.1 APT loading machine trafficking a pavement section.

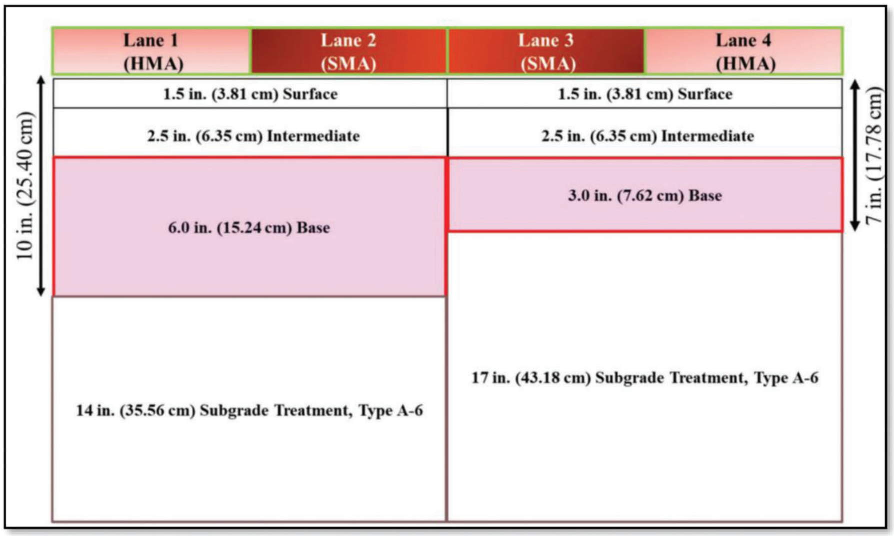

Figure 6.2 Layout of the test cross sections.

course. Both lanes have a 2.5-in. intermediate layer with a 3-in. asphalt base course. The asphalt layers were constructed on top of a layer of 14-in. and 17-in. lime-treated A-6 soil subgrade over the untreated A-6 subgrade. Both HMA and SMA surface mixes are Superpave 4-designed with a 9.5-mm nominal maximum aggregate size.

6.3 Lime-Stabilized Subgrade

An A-6 silt-clay soil, typical for subgrade soils in Indiana, was used for the subgrade. Lime was used to treat the A-6 soil to improve workability and load-bearing capacity. The maximum dry unit weight and optimum moisture content of the soil, as well as other properties are shown in Table 6.1.

The different phases of the subgrade construction are depicted in Figure 6.3. The APT pit was filled with A-6 soil from a nearby soil pit located in Lafayette, Indiana. The subgrade soil was placed in the test pit 24 in. below the surface in six lifts and had a total thickness of approximately 50 in. During placement, the lift thickness was limited to 8 in.

The exposed surface was thoroughly compacted with a hydraulic hand-operated sheep foot roller compactor. Lime-stabilization of the A-6 subgrade soil followed the placement of the untreated subgrade. The subgrade soil stabilization was conducted following INDOT specifications. As shown in Figure 6.3, the original A-6 soil was first placed inside the pit, and then 5% lime by weight was added and mixed using a soil mixer. Once the soil was thoroughly blended with the lime, it was compacted in lifts, and water was added between lifts to activate the lime. Soil compaction was performed using a roller compactor and a jumping jack tamper. For the detailed experimental program and sensors configuration

TABLE 6.1
Subgrade and lime soil modification design parameters

Subgrade Soil Information	
Property	**Value**
Maximum Dry Unit Weight	102 pcf
Optimum Moisture Content	18.6%
Borrow Pit Moisture Content	17%
Treated Soil Information	–
Subgrade Treatment Layer Thickness	17 in.
Number of Lifts per Layer	3 lifts
Compacted Lift Thickness	5.67 in./lift
Design Lime Content	5.0%
Lime Apparent Specific Gravity	2.60
Lime Slurry Content and Distribution Rate	–
Unit Volume per Lift per ft^2	0.472 ft^3/lift
Lime and Soil Weight per Lift per ft^2	48.17 lb/ft^2/lift
Lime Weight per Lift per ft^2	2.29 lb/ft/lift

refer to *Structural Evaluation of Full-Depth Flexible Pavement Using APT* (Nantung et al., 2021).

6.4 LWD Testing on Stabilized Subgrade

The lime-treated subgrade was cured for several days after construction to allow strength to develop. The subgrade was monitored for several days until it developed enough strength to continue the paving operations. Monitoring was conducted using lightweight deflectometer (LWD).

The LWD test was used to measure the materials in situ modulus values following ASTM E 2583, *Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)* (ASTM, 2020).

Figure 6.3 Construction of the subgrade layer.

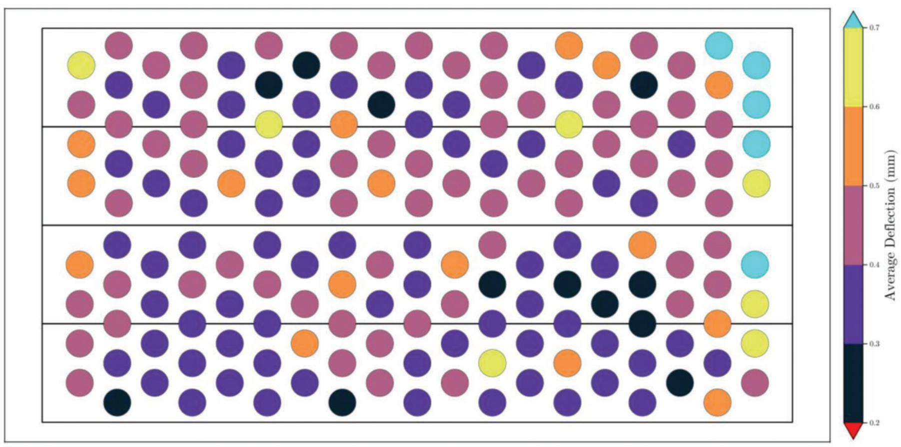

Figure 6.4 Locations and deflection from lightweight deflectometer tests on subgrade soil.

The LWD tests were performed at the lime-stabilized subgrade surface before the instrumentation installation. The locations and test results of the lightweight deflectometer tests on the subgrade soil are shown in Figure 6.4.

6.5 Correlation of FE Model and APT Experimental Results

Figure 6.5 provides the subgrade evaluation results (deflections) from LWD tests. As one can see, there is a reduction in the magnitude of deflections when comparing the 4-day vs. 7-day results. Also, a clear decreasing trend in average deflection with increasing time can be observed in Figure 6.5.

The significant variation in results across different testing locations on the same day of curing prompted a detailed analysis of the data distribution patterns for each testing day, excluding outlier values. Using the deflection values obtained from LWD experimental testing on the accelerated pavement testing (APT) section, a back calculated modulus of elasticity was used to develop the FE model. The average modulus of elasticity values for 1, 2, 4, and 7 days were calculated to compare with the experimental results from APT testing.

Subsequently, the experimental LWD deflections were compared with the FE simulation results. Despite these efforts, the comparison revealed a substantial discrepancy. As illustrated in Figure 6.6, the FE

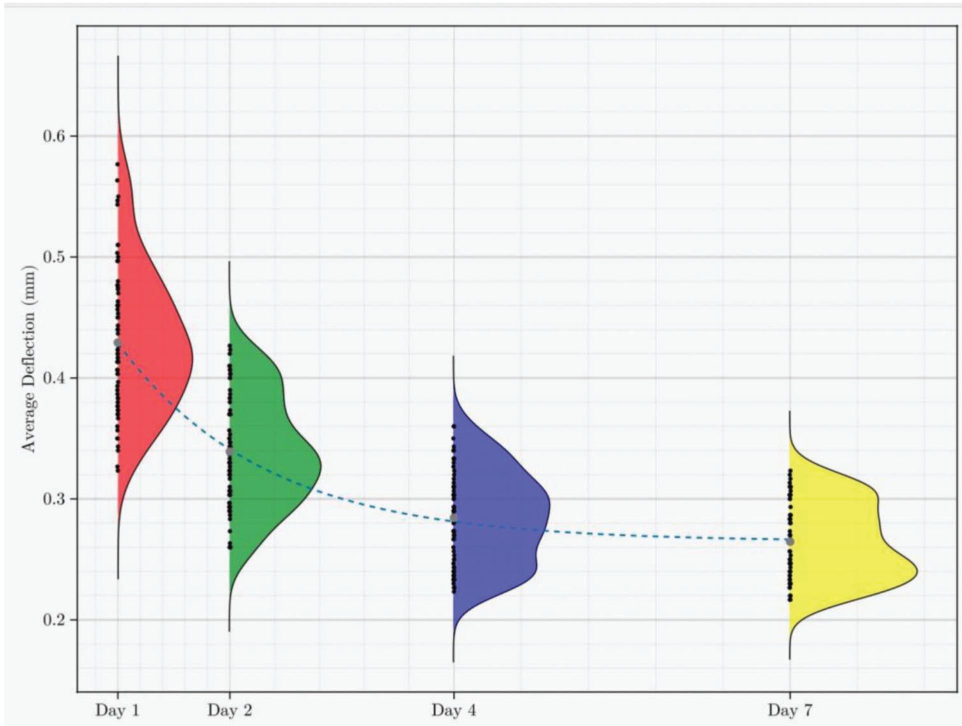

Figure 6.5 Deflection with curing time for a 17-in. subgrade.

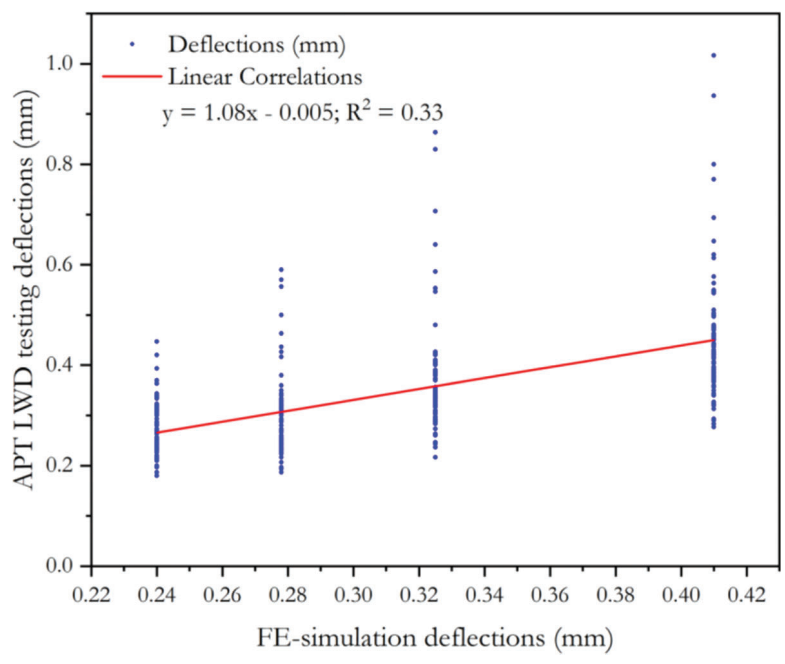

Figure 6.6 Comparison of APT and FE simulated LWD deflections.

simulation results did not align well with the experimental data. The root mean square error (RMSE) was calculated to be 0.33, indicating poor correlation between the simulated and observed results.

Therefore, the peak distributed values were then used to validate the FE model. As shown in Figure 7.1, the APT LWD test results were closely simulated by the FE model, yielding a root mean square error (RMSE) value of 0.98. This high correlation indicates the effectiveness of the FE model in accurately predicting LWD deflections, demonstrating its potential for use in performing test configurations through FE simulations. The viscoelastic-plastic material model effectively captures the material behavior, further supporting the reliability of the simulations.

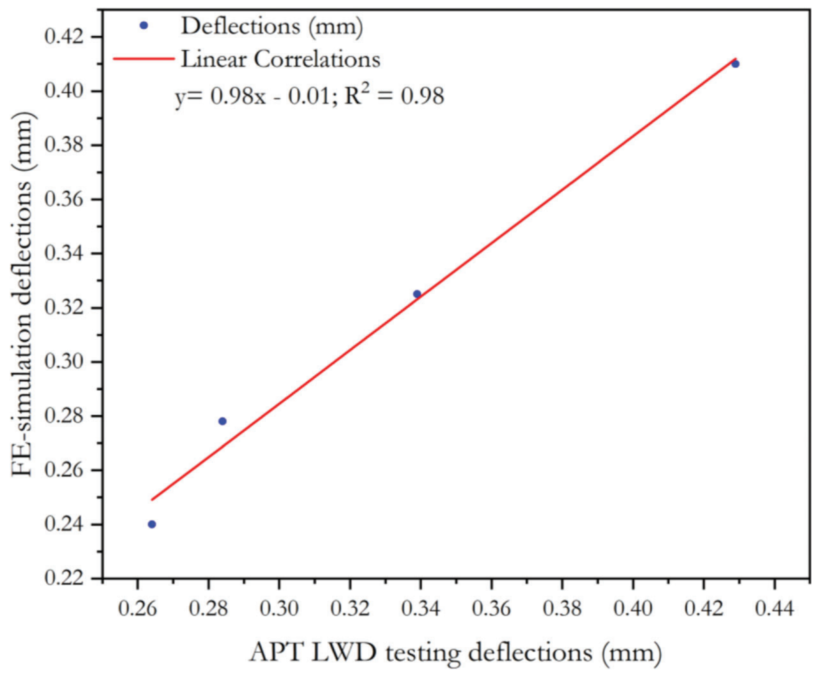

Figure 6.7 Comparison of APT (mean values) and FE simulated LWD deflections.

7. INTERPRETATION OF RESULTS

7.1 Equipment Effect on LWD Testing

LWD results obtained from Dynatest and Zorn instruments for different soils were used to compare the equipment factors (Simon, & LaBelle, 2023). To understand the factors affecting the results, only tests carried out under identical experimental conditions were considered for analysis. A wide range of materials was also involved to evaluate the performance of each equipment. Figure 7.1 shows the clustering plot of the LWD test deflections.

The deflections obtained from both instruments cluster into four distinct sections, represented by different colors: green, blue, pink, and yellow. As illustrated in Figure 7.1, the results from both instruments align closely at lower deflection values. However, at higher deflection values, significant discrepancies between the two instruments' results become apparent. Based on the data gathered, it seems that both instruments provide comparable measurements up to a deflection of 0.5 mm. Beyond this threshold, the discrepancies are very large and thus it seems necessary to determine which instrument yields true deflections.

7.2 Equipment Sensitivity

To determine which equipment more accurately assesses soil deflections, a comprehensive FE model was developed. The model closely replicates the experimental testing conditions, allowing for a detailed comparison between the results of the FE simulations and those obtained from Zorn and Dynatest light weight deflectometer equipment. The simulations incorporated various material conditions to ensure a thorough evaluation of the equipment's performance (Simon & Labelle, 2023).

The comparison revealed that the results from the FE simulations exhibited a strong correlation with the deflections measured by the Dynatest LWD equipment. Specifically, the root mean square error (RMSE) value between the FE model and the Dynatest measurements was 0.93 (Figure 7.2), indicating a high degree of accuracy and reliability.

In contrast, the deflections recorded by the Zorn LWD equipment showed a significantly lower correlation with the FE simulation results, with an RMSE value of only 0.27 (Figure 7.3). This suggests that the Zorn equipment may not be as effective in accurately measuring soil deflections under the tested conditions.

However, it is important to note that the current FE model has not been fully calibrated for the wide range of material conditions that might be encountered in practice. Therefore, while the initial findings suggest that the Dynatest LWD equipment provides measurements that are more consistent with the FE simulation results, this finding should be interpreted with caution. The current research does not provide definitive recommendations regarding the superiority of either piece of equipment.

To a more informed recommendation, further research is necessary. This should include testing a broader range of materials and under different test conditions to validate and refine the FE model. Only with additional data and a more comprehensive calibration of the FE model can a conclusive determi-

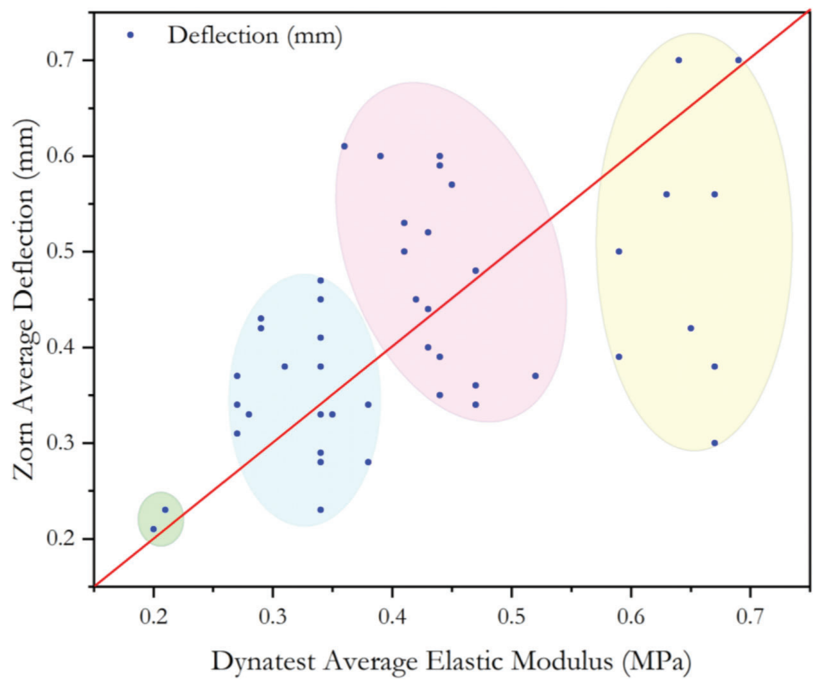

Figure 7.1 Clustered plot of Zorn and Dynatest LWD deflections.

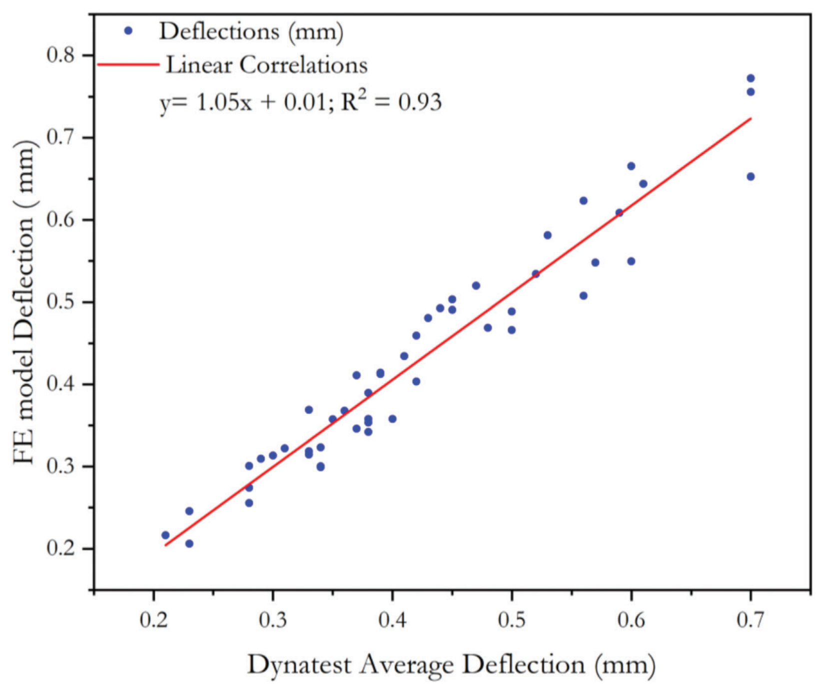

Figure 7.2 Comparison of Dynatest and FE simulation LWD deflections.

nation be made about the accuracy and reliability of the Dynatest and Zorn LWD equipment. This future work will be critical in ensuring that the chosen equipment provides the most accurate and reliable measurements for assessing soil deflections and the elastic modulus of the materials.

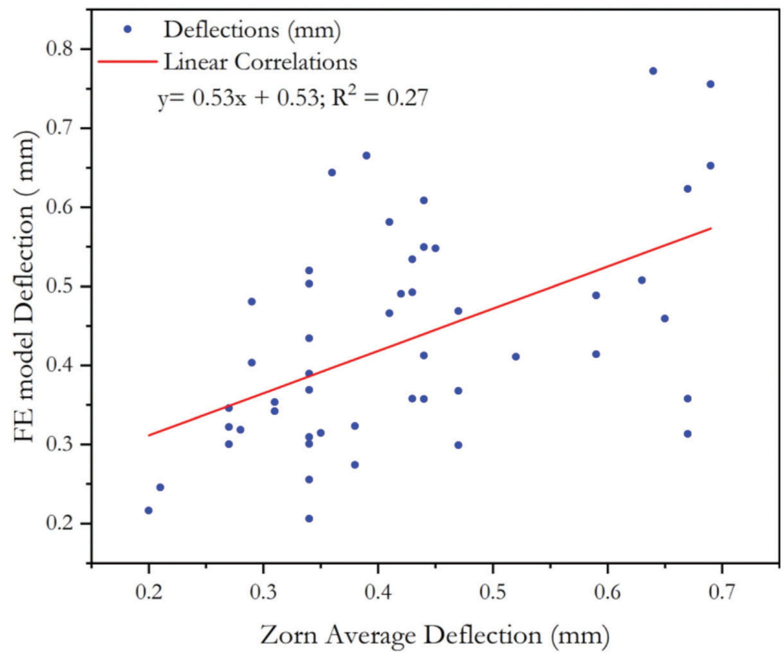

Figure 7.3 Comparison of Zorn and FE simulation LWD deflections.

8. CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

Based on the findings presented in this study, the following conclusions are drawn.

- The integration of the viscoelastic plastic model into the modeling of LWD measurements helps with the interpretation of the results and enables more accurate and reliable predictions of pavement and soil behavior under impulsive loading conditions.
- The viscoelastic plastic model consideration of the hysteresis effect, observed during impulsive loading in LWD tests, provides a better representation of material response over time. This results in an improved understanding of the dynamic behavior of pavements and soils.
- The close alignment between results derived from finite element method (FEM) simulations and experimental testing underscores the accuracy and applicability of the viscoelastic plastic model. This further affirms its potential in capturing the material's time-sensitive response.
- FE models can be used for optimizing pavement design, evaluating performance, and forging sustainable infrastructure solutions. By averting the overestimation of subgrade resilient moduli, the model contributes to prevent premature pavement failure, thereby prolonging the lifespan of transportation infrastructure.
- The new laboratory-scale LWD experimental setup is equipped with sensors and is calibrated well for static and dynamic loadings. The facility has the potential to test controlled sections with varying material and environmental conditions and, therefore, can be used to develop more reliable deflection criteria.
- Initial results suggest that Dynatest LWD equipment provides more reliable results compared to Zorn LWD equipment. This comparison is based on FE simulations; however, further laboratory testing is required to make support the finding. This report does not suggest that any changes need to be made in ITM508 at this stage, as a more comprehensive evaluation is required before making recommendations.

8.2 Future Work

Building on the findings and advancements made in this study, several areas for future work have been identified to further enhance the understanding and application of LWD testing and the viscoelastic plastic model in geotechnical and pavement engineering.

8.2.1 Expanded Material Evaluation

The testing box setup, a pivotal component of the research, could be used to evaluate a broader range of subgrade materials currently used in INDOT construction and research projects. Such expanded evaluation would contribute to achieving a comprehensive understanding of the behavior of various materials under different loading and environmental conditions. By including a diverse array of natural, modified, and stabilized materials, more universally applicable deflection criteria could be developed.

8.2.2 Refinement of the Viscoelastic Plastic Model

Future work should focus on further refining the viscoelastic plastic model by incorporating a wider variety of material types and simulating different compaction conditions. This effort could involve the following.

- Extending the model to include additional soil and pavement material properties.
- Simulating a range of environmental conditions such as temperature and moisture variations to understand their impact on material behavior.
- Enhancing the model's predictive capabilities by integrating real-time data from field measurements and laboratory tests.

These refinements aim to make the model more robust and applicable across a wide spectrum of real-world scenarios, ensuring its effectiveness in diverse construction projects.

8.2.3 Integration of Advanced Sensing Technologies

Active integration of advanced sensing technologies will achieve a more nuanced capture of viscoelastic plastic behavior. These technologies include the following.

- *Fiber Bragg Grating (FBG) Sensors:* To provide high-precision strain measurements, enabling detailed monitoring of material responses under LWD testing.
- *3D Snapshot Laser Sensors:* To capture deflection profiles and surface deformations, facilitating a better understanding of the deflection basin and boundary effects.

These sensors could be used to explore realistic and practical correlations between deflection measurements and the mechanical properties of the materials under study, leading to more accurate and reliable deflection criteria.

8.2.4 Comprehensive Field Studies

To validate the laboratory findings and model predictions, comprehensive field studies should be conducted. These studies could involve the following.

- Implementing the refined LWD testing protocols and viscoelastic plastic model in active construction sites.
- Comparing field data with laboratory results to identify any discrepancies and refine the model further.
- Conducting long-term monitoring of pavement performance to assess the practical impact of the developed deflection criteria.

The integration of the viscoelastic plastic model in LWD measurements has been a significant accomplishment from this project. The findings presented attest to the model's effectiveness in forecasting the dynamic behavior of pavements and soils. With further integration of advanced sensing technologies, diverse material research, methodological improvements, and comprehensive field studies, a substantial contribution to LWD testing is likely. This will ensure enhanced performance and resilience of future transportation infrastructures.

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About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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