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Evaluation of Undulation Damage through Finite Element Simulation and Experimental Validation

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Abstract

A Finite Element (FE) modelling method incorporating experimental validation is introduced to simulate the pavement road undulation response of two-dimensional Unbound Granular Materials (UGM). UGM are frequently used in flexible paving roads to accommodate dynamic loads with fluctuating frequency. Simulations were conducted for 08-18 kg using both implicit and explicit dynamic analyses. Predictions were juxtaposed with actual outcomes, demonstrating that two-dimensional (2D) modelling of the UGM yields a predicted damage area that closely matches the experimental results.

Keywords
Pavement Undulations, Finite Element Modelling, Experimental Validation.

1. Introduction
Pavement undulation resulting from the substantial loads imposed by heavy trucks is a significant issue that accelerates road degradation and poses serious safety concerns for motorists (Pais et al., 2013). Traditional pavement design methodologies typically rely on static load assumptions that often fail to account for the complex dynamic effects of real-world vehicle movement (Kurakina & Evtiukov, n.d.). This study aims to address these shortcomings by: Developing a two-dimensional finite element (FE) model using ABAQUS, which simulates the interactions between tyres and pavement surfaces under dynamic conditions; validating the model's accuracy through comprehensive testing that encompasses 437,184 experimental loading cycles, utilising loads that range from 8 to 18 kg to replicate real-world conditions. Modern road infrastructure is increasingly burdened by the cumulative impact of heavy truck traffic, leading to pavement distress such as rutting, cracking, pronounced undulations, and other forms of damage (Cui et al., 2024; Chen et al., 2022; Jing et al., 2025). Among these issues, pavement undulation, especially prevalent near stop signs, traffic signals, and zones with frequent deceleration, is a significant indicator of roadway deterioration. This undermines ride quality and poses hazards for drivers and passengers. Traditionally, pavement design relies heavily on static load models that assume vehicle weights are constant and evenly distributed across the pavement surface. While these established practices have supported decades of highway engineering, they inadequately reflect

the dynamic realities of moving vehicles (Chen et al., 2025; Llopis-Castelló et al., 2020). Trucks impose variable loads due to factors such as suspension movement, tyre deformation, and changes during braking and acceleration. These dynamics create concentrated stress patterns within the pavement layers, often leading to an underestimation of the actual impact on pavement life and performance. This study endeavours to address these limitations by embedding finite element (FE) analysis into the evaluation process, thereby enabling more precise simulation of the dynamic loading conditions pavements experience. Specifically, it introduces a two-dimensional FE model developed in ABAQUS that replicates the complex tire-pavement interactions under diverse vertical loading scenarios, reflecting heavy truck operations. The model's predictions are rigorously validated against data from 437,184 laboratory loading cycles across a range of conditions that mirror real-world heavy truck operations.

1.1 Objectives

The objective of this study is to develop a 2D FE model in ABAQUS that simulates the mechanical interactions between a moving tyre and a flexible pavement structure. The importance of this work lies in validating the predictive accuracy of the FE model through comprehensive experimental testing comprising 437,184 loading cycles. A key focus of the analysis will be the pavement response and distress mechanisms—such as rutting, cracking, and undulations—predicted by the validated model under dynamic loads ranging from 8 to 18 kg.

1.1.1 Model Development & Parameterisation

Define appropriate material constitutive models, including hyperelastic for the tyre, viscoelastic for asphalt layers, and elastic for base and subgrade layers, within the 2D FE framework. Establish contact definitions and boundary conditions to accurately replicate the dynamic rolling and loading of a tyre on a pavement surface. Parameterise the model using loading conditions that simulate real-world heavy truck traffic, with emphasis on the specified load range.

1.1.2 Experimental Validation & Calibration

Design and execute a laboratory or field-testing protocol capable of applying 437,184 controlled loading cycles on a pavement section. Measure essential pavement responses—such as stress, strain, and deflection—under loads of 8, 10, 12, 14, 16 and 18 kg for direct comparison with model outputs. Calibrate the FE model by iteratively adjusting input parameters to minimise discrepancies between simulated results and experimental data.

1.1.3 Analysis & Application

Utilise the validated model to quantify critical pavement responses, including vertical compressive strain at the top of the subgrade and tensile strain at the bottom of the asphalt layer, across the entire range of applied loads. Correlate the simulated stress-strain regimes with common pavement failure modes, particularly rutting and fatigue cracking. - Demonstrate the model's effectiveness as a predictive tool for assessing the long-term performance and damage accumulation in pavements subjected to repeated heavy traffic loads. This structured approach aims not only to advance understanding of mechanical responses in pavement structures but also to contribute valuable insights into the preservation and longevity of pavement systems under sustained vehicular stress.

2. Literature Review

FE modelling of tyre-pavement interactions, focused on dynamic 2D modelling in ABAQUS and extensive experimental validation.

2.1. Introduction to Tyre-Pavement Interaction Modelling

The interaction between tyres and pavement is a critical factor in the effective analysis of road distress, energy consumption, and vehicle performance dynamics. As infrastructure ages and heavy traffic volumes increase, it becomes increasingly vital to develop a comprehensive understanding of these interactions. This knowledge is essential for developing durable, resilient pavement designs that can withstand the demands placed on them. In traditional pavement design methodologies, tyre loads are often simplified, typically represented as uniform static pressures. However, this approach overlooks the complex nature of the forces at play during actual vehicle operation. Tyres exert varying pressures that can change in response to factors such as speed, load distribution, and road conditions, resulting in different stress patterns on the pavement. Recognising and accurately modelling these dynamic interactions is crucial not just for improving pavement longevity but also for minimising energy use in transportation and enhancing overall road safety. Therefore, a more nuanced approach to understanding tyre-pavement interaction is essential for creating sustainable infrastructure that can accommodate modern traffic demands.(Wang et al., 2013; Király et al., 2022a; Chen et al., 2025). However, real-world loads are dynamic and non-uniform, generating complex stresses that directly cause distress, such as rutting and cracking. This highlights the need for advanced modelling tools to accurately capture these dynamic interactions.

2.2 Evolution of Numerical Modelling Techniques

To address the significant financial burden and constraints of conducting physical experiments, researchers have increasingly turned to computational methods. These advanced techniques not only reduce overall costs associated with experimentation but also enable greater flexibility and scalability in research. By utilising simulations and modelling, scientists can explore a vast range of scenarios and variables that may be impractical or impossible to test in a laboratory setting. This shift towards computational approaches has become a pivotal strategy in various fields, enabling the exploration of complex systems and phenomena with greater efficiency and accuracy (Yu et al., 2026). FE, particularly when coupled with sophisticated software such as ABAQUS, has emerged as a widely accepted technique across various engineering applications. One of the primary challenges in this field is achieving an optimal balance between model fidelity, essentially, the accuracy and detail of the model, and the computational costs of running simulations. Research indicates that while highly detailed three-dimensional tyre models can provide accurate representations of tyre behaviour and performance under various conditions, they often require significant computational resources. This can make them prohibitively expensive for dynamic simulations, thereby posing a dilemma for engineers and researchers who must determine the level of detail required for their analyses without incurring high computational costs. (Király et al., 2022b). This sets the foundation for investigating more efficient two-dimensional (2D) models or simplified three-dimensional (3D) representations (Liu et al., 2024). The aim is to enhance computational efficiency and enable faster analysis while preserving the essential dynamics of the system under study. By focusing on these more streamlined models, we may be able to reduce complexity without compromising the accuracy needed for meaningful insights. This approach enables easier manipulation and visualisation of data, ultimately leading to more robust, practical applications across fields such as engineering, computer science, and the physical sciences. To analyse the impact of tyre load on asphalt mixtures, researchers in France conducted a two-dimensional simulation using Discrete Element Modelling (DEM) tailored for the wheel-tracking test. Furthermore, they expanded the investigation by conducting a three-dimensional virtual wheel-tracking simulation, employing DEM techniques. It's noteworthy that current DEM frameworks primarily aim to replicate the controlled conditions of laboratory tests on asphalt samples, largely because of the considerable computational demands of more complex simulations. As a result, the boundary loading conditions in these models are often uniform and simplified, potentially overlooking the nuanced complexities of real-world scenarios. (Ge et al., 2022). The following table, labelled Table 1, presents a summary of the significant modelling FE methods discussed in the literature.

Table 1. Modelling Approach

FE Modelling Method	Key Features and Findings	Reference
Complex vs. Simplified 3D FE Models	A model of a radial truck tyre was streamlined by decreasing the number of elements in its design. This simplification enabled the model to perform dynamic analyses effectively; however, it exhibited characteristics more akin to those of a diagonal tyre in contact with the ground. Notably, despite these differences in model behaviour, both the original and the simplified models produced comparable results for pavement stress measurements at depths of 5 to 8 centimeters.	(Király et al., 2022b)
3D Dynamic Rolling FE Model in ABAQUS	A validated FE model was utilised to analyse rolling energy consumption in detail. The findings indicate that tyre load exerts the greatest influence on energy consumption, followed by tyre pressure, friction coefficients, pavement stiffness, and vehicle speed. The analysis concludes that energy consumption increases with higher tyre load and friction, but it can be mitigated by optimising tyre pressure or by employing stiffer pavement materials.	(Liu et al., 2024)

Multiscale FEM-DEM Coupling	The integration of FE for modelling the tyre and the Discrete Element Method (DEM) for the pavement provides a comprehensive analysis of the interaction between these two components. This approach allows for the detailed capture of non-uniform contact stresses that occur during tyre-pavement interaction, which is critical for understanding the distribution of forces. Furthermore, by leveraging DEM, the internal responses of the asphalt mixture at the particle scale can be analysed. This granular approach reveals the underlying mechanisms contributing to surface degradation, offering insights into how conditions such as load distribution, temperature fluctuations, and material properties affect the longevity and performance of pavements. Overall, this combined modelling technique enhances the ability to predict wear and failure processes, ultimately informing better design and maintenance strategies for roadway systems.	(Ge et al., 2022)

2.3 Pavement Road Heterogeneity

One consideration in traditional FE is its assumption that asphalt behaves as a uniform, homogeneous material, overlooking its inherent complexities. To overcome this limitation, researchers have begun integrating FE with DEM. This approach provides a refined representation of asphalt's granular structure, enabling detailed analysis of how damage initiates at the particle level. By utilising this coupling, engineers can gain valuable insights into the complex interactions and behaviour within asphalt mixtures, ultimately leading to improved designs and better performance predictions for asphalt in various applications.

2.4 Factors and Response Analysis

The speed of the vehicle and the weight it carries play a crucial role in determining the level of noise produced, as well as the underlying acoustic processes responsible for that sound generation (Yu et al., 2026). Research has demonstrated that tyre load is the most influential factor affecting both pavement response and energy consumption during rolling. This means that the vehicle's weight, distributed through its tyres, plays a crucial role in how the pavement responds under load and in how efficiently the vehicle moves (Liu et al., 2024). The uneven distribution of contact stresses, both vertical and tangential, plays a crucial role in tyre performance. These stresses, particularly concentrated at the tyre edges, are significant contributors to the development of near-surface cracking and rutting. Such damage affects tyre longevity and compromises vehicle safety and handling by creating unstable surfaces. Understanding this distribution is essential for improving pavement road design and performance under various driving conditions (Ge et al., 2022).

2.5 Research Gaps and Proposed Advancements

Numerous models are validated primarily under constrained static conditions or in low-cycle scenarios, where external influences and changes are minimal. This limited testing environment may not fully capture the models' dynamic behaviour and responses under more varied and demanding conditions. (Liu et al., 2024; Yu et al., 2026). Our proposed validation study, which encompasses an extensive analysis of 437,184 loading cycles, is designed to address a crucial requirement for evaluating long-term performance. This comprehensive assessment was conducted under realistic conditions that simulate cumulative damage scenarios, thereby enabling a better understanding of how materials and structures behave over extended periods of use. By examining numerous loading cycles, we aim to collect data to inform future designs and improvements, thereby enhancing durability and reliability in practical applications. There exists a clear trade-off between the complexity of 3D models and the practicality of performing dynamic analysis. As model complexity increases, the computational resources and time required for analysis also rise, often making it challenging to obtain meaningful results without overloading the system. Balancing these two factors is essential for effective and efficient dynamic analysis.(Király et al., 2022b). Our development of a 2D FE model in ABAQUS specifically addresses a critical gap in the current research landscape. This model aims to provide an effective pathway for conducting dynamic simulations that balance both efficiency and accuracy. In previous studies, factors such as load and speed have often been examined in isolation, limiting understanding of their interdependencies with material behaviour. However, our approach emphasises the need for an integrated analysis spanning a comprehensive load range of 8 to 18 kg. By doing so, we aim to establish a direct correlation between the dynamic response of the materials and their associated failure modes, including rutting and undulations. This integrated methodology seeks to enhance the predictive capabilities of our simulations and to provide valuable insights into the mechanisms underlying material degradation under varied loading conditions. By linking dynamic performance to these critical failure modes, we aim to inform improved design and material selection strategies across the industry.

3. Methods

3.1. FE Model Setup

The tyre geometry is a two-dimensional, axisymmetric shape with a radius of 57 millimeters. This dimension is derived from scaling the specifications of a 59/80R57 tyre model, ensuring a precise fit and performance characteristics. The pavement structure is a layered system consisting of two distinct layers. The upper layer is 100 millimeters of asphalt, providing a durable, smooth surface, while the lower is 200 millimeters of granular base material, offering stability and support for the asphalt layer above. The asphalt material is modelled using an elastoplastic approach based on the Drucker-Prager yield criterion. This model incorporates a friction angle (β) of 30 degrees and a dilatancy parameter (d) of 0.1, which helps simulate the material's behaviour under various loading conditions. The tyre is modelled using the hyperelastic Yeoh model, which accurately captures the tyre's material response under deformation. The key parameter for this model is C_{10}, set to 1.2 MPa, which enables a realistic representation of the tyre's elastic properties. The base of the model is fixed using an encastre boundary condition, ensuring that it remains completely restrained against translation and rotation. The model's sides are supported by roller supports, allowing vertical movement while restricting horizontal displacement, thereby providing a realistic constraint for the analysis.

3.2 Loading and Meshing

The study involves a load range with experimental scaling yielding figures between 8 and 18 kg. For the mesh configuration, we are utilising adaptive Arbitrary Lagrangian-Eulerian (ALE) remeshing with a surface bias of 240 elements. The analysis employs two types of elements: CPE4R elements to represent the asphalt layer and CPE3 elements to represent the base layer.

3.3 Experimental Validation

The experimental setup consists of small-scale pavement samples, each measuring 600 mm in length, 200 mm in width, and 300 mm in height. The system operates at a cyclic loading frequency of 1.5 Hz, selected to match field data and accurately replicate real-world conditions. While the specific loading conditions are detailed in Section 3.4, it is important to emphasise that dynamic loading is applied via a Reference Point (RP) located precisely at the tyre's center. This thoughtfully designed configuration enables both vertical and horizontal force control, effectively mimicking the interactions that occur during rolling and braking on pavement surfaces.

3.4 Loading and Simulation Procedure

To replicate the conditions encountered in real-world truck movements, the FE model incorporates dynamic loading at the tyre-pavement interface, employing a rigorously controlled load history. This simulation effectively captures the dynamics of vertical compression and lateral sliding that arise during vehicle deceleration and are significantly influenced by frictional interactions between the tyres and the road surface. These variables play a crucial role in the formation of pavement undulation, thereby enhancing our understanding of pavement performance under different loading scenarios. This comprehensive approach elucidates the critical factors affecting pavement durability and integrity.

3.4.1 Loading Method

The tyre testing setup is centred on RP, with a strategically placed Reference Point (RP) at the tyre's center. This RP is kinematically linked to the tyre body, enabling the application of external loads while preserving the tyre's geometric integrity. To accurately simulate the conditions experienced by heavy trucks, a series of vertical loads ranging from 8 to 18 kg is applied using an incremental sinusoidal waveform. This loading pattern reflects the repeated stress cycles that tyres encounter in real-world scenarios. The load magnitudes are calibrated to represent the dynamic responses observed in full-scale heavy trucks, with mass-scaling ratios ranging from 78 to 176 kg in laboratory settings, corresponding to field weights ranging from 10 to 100 tonnes. In addition to vertical loads, lateral displacement is implemented through horizontal forces or displacements at the reference point (RP). This approach simulates scenarios involving braking or low-speed deceleration, such as when vehicles approach a stop sign or navigate an intersection. As a result, the tyre experiences sliding contact with the pavement, thus replicating the shear-induced deformations that affect the tyre surface. The simulation protocol involves conducting five complete loading cycles at each specified load level, enabling a detailed analysis of the tyre's stress-strain behaviour under consistent, repeated conditions. For experimental validation, a comprehensive total of 437,184 cycles is executed, ensuring a thorough assessment of the tyre's performance. This testing framework enables fine-tuning of FE responses to align them with observed peak values, deformation trends, and the temporal progression of rutting depth.

3.4.2 Step Settings and Time Integration

The analysis is conducted using a dynamic, implicit and explicit time-integration scheme within the ABAQUS/Explicit software environment. This approach is particularly well-suited to scenarios involving high-speed loading conditions and complex contact mechanics. To ensure numerical stability throughout the simulation, a very small time increment of approximately $(10)^5$ seconds is used. Additionally, mass-scaling techniques have been adopted to significantly reduce the computational time required for the analysis. These techniques involve artificially increasing the mass within the model domain; however, it is crucial to ensure that the adjustments remain within quasi-static limits. This is achieved by carefully monitoring the magnitudes of the inertial forces generated during the simulation, thereby confirming that the modified mass does not adversely affect the physical accuracy of the results. By employing these methods, the analysis maintains realistic strain rates, allowing for a reliable representation of the material behaviour under specified conditions.

3.5.3 Contact Interactions and Friction

The interaction between the tyre and the asphalt surface is characterised by direct surface-to-surface contact at the pavement's top layer. To accurately model friction between rubber and asphalt, we use a Coulomb friction coefficient of 0.7. This value effectively simulates dry-weather conditions, where grip and traction between the tyre and the road surface are crucial for vehicle performance. The contact algorithm employs a penalty-based method that allows sliding motion between the tyre and pavement without causing excessive penetration or sticking. This mechanism ensures a realistic and reliable simulation of tyre-roadway interactions under various driving conditions.

3.5.4 Mesh and Convergence

In this analysis, we employ axisymmetric quadrilateral elements, specifically the CAX4R type, which uses reduced integration to model both the pavement and tyre domains. To achieve precise results, a finely refined mesh is used in the critical tire-pavement contact zone, with element sizes of approximately 1 mm. This level of mesh refinement provides an accurate representation of interactions at the interface. In contrast, a coarser mesh is used in regions distal to the contact zone to improve computational efficiency while maintaining the simulation's overall integrity. As part of the convergence assessment, we systematically monitor key output variables, including vertical deformation, stress distribution, and plastic strain levels. This monitoring is crucial to ensure that these variables stabilise throughout the simulation cycles, thereby confirming the reliability and accuracy of the results.

3.5.5 Experimental Setup

A total of six pavement structure specimens were prepared, in accordance with the specified proportions outlined in industry standards. The decision to utilise six specimens was carefully considered to ensure accurate outcomes. This sample size was deemed sufficient for conducting an undulation experiment, as it allowed the collection of data necessary to draw reliable, valid, and repeatable conclusions. Resource constraints also influenced this decision; although increasing the number of specimens was feasible, it was determined that more than six would not significantly improve results specific to the undulation experiments. Each of the six specimens was systematically designed to evaluate their response to loads ranging from 08 to 18 kilograms, for a detailed view of the preparation process for each specimen and the resulting material reactions observed during testing. The flowchart in Figure 1 outlines the research methodology employed in this paper. It illustrates the systematic approach to the method and provides a brief outline of the experimental plan to achieve the set objectives.

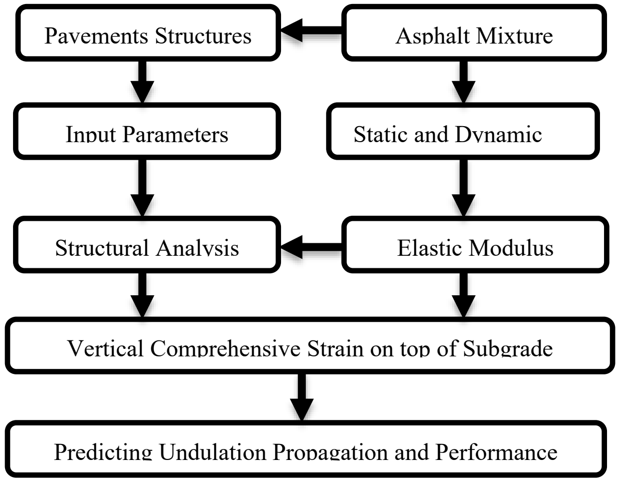


Figure 1. The Algorithm for Research Methodology

3.5.6 Laboratory Experiment Set-Up for Road Response

All tests were conducted in a clean, well-ventilated laboratory environment in the Department of Mechanical and Mechatronic Engineering of the Cape Peninsula University of Technology, ensuring optimal conditions for accurate results in accordance with ISO 17025 standards (Anon, n.d.). The testing setup utilised a specialised test rig, carefully constructed in the laboratory at Cape Peninsula University of Technology. This test rig was designed to simulate real-world conditions and assess various performance metrics of road materials.

The varying loads, ranging from 8 to 18 kg, were applied at specified intervals, producing discernible, measurable undulations in each specimen. The experiment commenced with the application of an 8 kg weight, after which the wheel structure was released, allowing it to exert a calculated force onto the specimen. The wheel carrier moved forward at 1.38 m/s (5 km/h), maintaining this pace until it reached the designated endpoint. Upon reaching the fixed end, the specimen was unloaded, after which the wheel structure was elevated to enable it to move backwards to the start position again. The initial cycle, often referred to as a complete pass, occurs when the wheel structure moves from the start to the end position. This motion generates a dynamic force that is applied to the specimen, initiating the testing process. This cyclic process was replicated over 11 days, with each day consisting of 8 hours of continuous operation. It was not until this period that the material's undulations became visible and quantifiable.

The wheel's forward motion was intentionally designed to mimic real-world scenarios in which vehicles typically travel in one direction along a designated roadside. This strategy replicated conditions and prevented inadvertent flattening of wave undulations during the backwards motion. Following each cycle, the specimen was reloaded to its initial start position, and the procedure was repeated until the resultant wave undulations exhibited a brief rise. The amplitude was effectively transmitted through the specimen.

The threshold of strain that a specimen can sustain before the emergence of wave undulations is associated with the magnitude of the applied load and the total number of cycles endured. A 10 kg weight was utilised for loading over 11 days, with 8 hours of application each day. This procedure was similarly implemented for loads of 12 kg, 14 kg, 16 kg, and 18 kg. The specimens demonstrated incomplete fractures; rather than breaking, they exhibited a range of wave-like undulations that responded to dynamic loads and varied cycles. These undulations formed in harmony with the rubber-hard tyre, demonstrating their responsiveness to the external forces acting on them.

The undulations were more pronounced when the aggregate material was dry, whereas they progressed significantly more slowly under saturated conditions. Additionally, the relatively low speed of 1.38 m/s contributed to the development of these wave patterns. The load cell's digital interface quantifies the load applied to the specimen. Each specimen was specifically crafted to fit the dimensions of the testing rig's steel box, which measures 600 mm (length) x 200 mm (breadth) x 200 mm (height).

4. Data Collection

4.1 Experimental Data Collection (Phase 1)

This phase focused on developing a reliable benchmark for the analysis of the mechanical behaviour of Unbound Granular Material (UGM).

4.1.1 Material Characterisation

We assessed several key geotechnical properties of the UGM, including particle size distribution, density, and moisture content. These essential parameters were obtained through a series of standardised laboratory tests, which provided crucial data inputs for the Finite Element (FE) model.

4.1.2 Test Setup and Instrumentation

To simulate real-world conditions, we constructed a laboratory pavement test section featuring a UGM layer. The setup was designed with precision, incorporating sensors strategically placed throughout the pavement. We embedded Linear Variable Differential Transformers (LVDTs) to measure deflection and strain gauges to monitor stress responses in the pavement, thereby capturing the material's dynamic behaviour under load.

4.1.3 Controlled Loading Protocol

A dynamic loading system was employed to apply controlled loads to the test section, ranging from 8 kg to 18 kg. These loads were applied at varying frequencies, closely mimicking the actual traffic conditions that UGM would experience in the field. Throughout the loading process, we recorded the magnitude of the applied load, the application frequency, and the resulting pavement responses, including deflection and strain, synchronously to ensure accurate data collection.

4.1.4 Post-Test Measurement

After completing the testing phase, we assessed the physical damage incurred on the UGM surface. This included careful measurements of any visible damage, such as rutting and deformation zones. The data collected from these measurements served as the primary experimental results, which were subsequently compared directly with predictions from the FE model, enabling a comprehensive evaluation of the material's performance.

4.2 Numerical Simulation Data Generation (Phase 2)

This phase focused on the comprehensive development and implementation of the computational model, employing a systematic approach to design, test, and refine it to ensure its accuracy and effectiveness in simulating the relevant processes. This included gathering necessary data, selecting appropriate algorithms, and conducting various simulations to validate the model's performance before full-scale deployment.

4.2.1 Model Development

A comprehensive two-dimensional (2D) Finite Element model was developed using the commercial software ABAQUS, specifically tailored to accurately replicate the geometry of the experimental test section. This geometry was critical, as it ensured that all relevant dimensions and intricate features, such as notches, holes, and varying thicknesses, were meticulously incorporated into the model. The modelling phase began with a thorough definition of material properties, including key parameters such as elasticity, plasticity, and density, thereby enabling the simulation to realistically depict material behaviour under stress. Furthermore, boundary conditions were carefully established to replicate the constraints and loading conditions encountered in the experimental tests, thereby providing an accurate representation of the physical phenomena. To enhance the accuracy and efficiency of the simulations, various mesh configurations were systematically explored. This involved refining the mesh to ensure that areas of high stress concentration or complex geometry were sufficiently detailed while optimizing computational resources. The chosen mesh configuration aimed to balance accuracy and computational cost, enabling faster simulations without compromising the integrity of the results. By aligning the Finite Element model closely with the actual test section, the approach was designed to facilitate robust analysis of the underlying mechanics and behaviours observed during experimentation. The insights gleaned from this detailed modelling process were expected to contribute significantly to understanding the phenomena at play, ultimately supporting the development of more effective engineering solutions.

4.2.2 Input Parameters
The material properties established in Phase 1 were utilised to define the Unsaturated Granular Material (UGM) layer within the model. This involved applying constitutive models ranging from linear elasticity to more sophisticated nonlinear frameworks, including the Drucker-Prager model.

4.2.3 Simulation Execution
Two types of dynamic analyses were conducted to evaluate the system's response under different loading conditions.

4.2.3.1 Implicit Dynamic Analysis
This approach is particularly suited for scenarios involving low-frequency, long-duration events. It provides a stable solution by iteratively solving the equations of motion, thereby enabling effective capture of the gradual response of structures under sustained loads.

4.2.3.2 Explicit Dynamic Analysis
In contrast, this analytical method is particularly well suited to examining high-frequency, short-duration impacts, which are often observed during abrupt loading events. To achieve this, the approach incorporates a sophisticated time-stepping technique that dynamically computes the system's response over time. This enables the effective capture of rapid changes and transient effects during such events. To ensure consistency and reliability in the results, simulations for both the dynamic analyses and the corresponding experimental setup were conducted using the same range of loading parameters, specifically between 08 and 18 kg. By maintaining this uniform load range, the findings obtained from the dynamic analyses can be directly compared with the experimental outcomes, thereby validating the accuracy and relevance of the simulations in reflecting real-world behaviour.

4.2.4 Output Extraction
The finite element (FE) software produced a range of data outputs that provided valuable insights into the material behaviour under various loading conditions. These outputs included detailed stress distributions that illustrated internal stresses throughout the material and deformation contours that depicted the extent and nature of deformation during the analysis. Additionally, the software predicted zones of Equivalent Plastic Strain (PEEQ), which are critical for identifying areas where the material has undergone plastic deformation beyond its elastic limits. To assess the impact of these findings, we quantified the predicted permanent deformation, commonly referred to as the "damage area." This was accomplished by analysing the stress and strain results in conjunction with established failure criteria, enabling a comprehensive comparison of the damage area with expected performance metrics. This detailed examination aids in assessing the material's durability and reliability in practical applications.

The data collection for this study was organised into two primary phases: experimental testing to obtain empirical response data, and numerical simulation to generate computational predictions for validation. The methodology is illustrated in Figure 2.

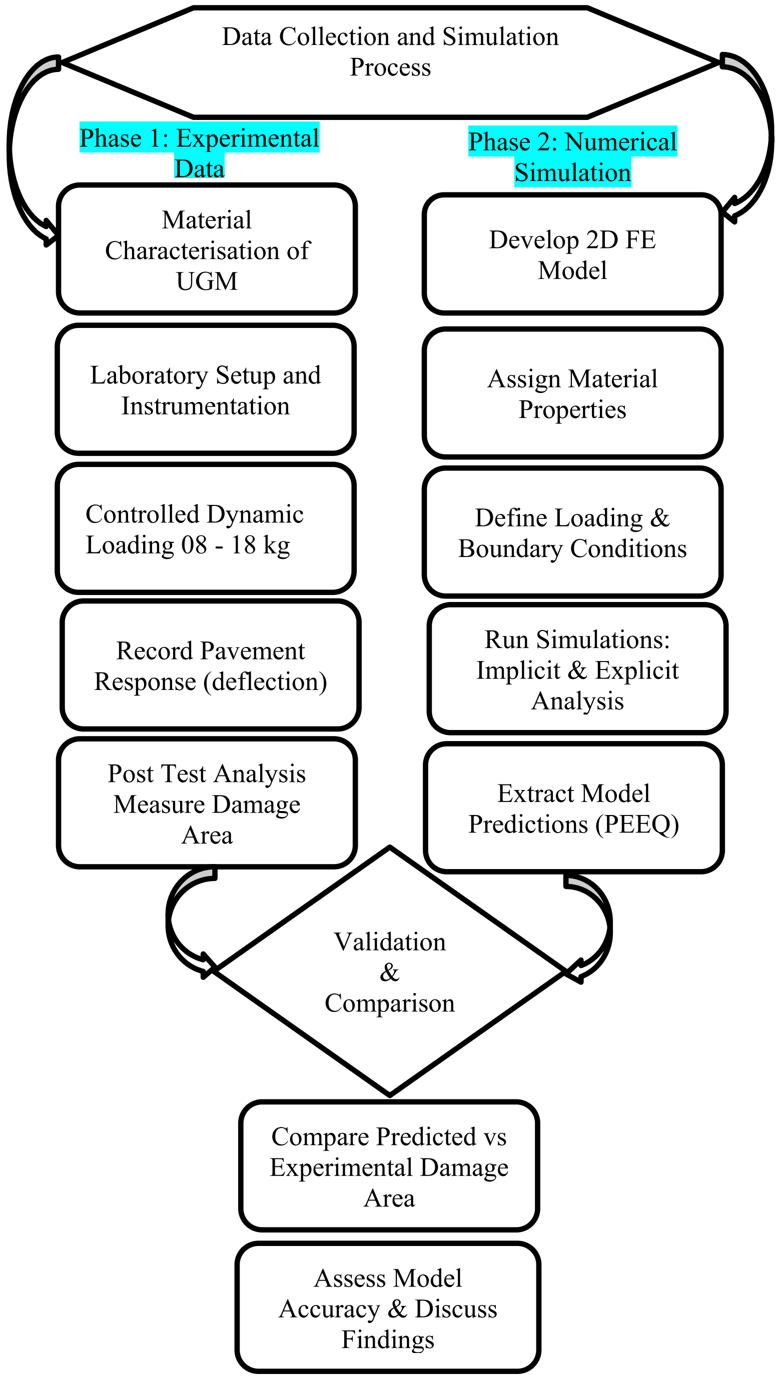


Figure 2. Data Collection and Simulation Process Workflow

5. Results and Discussion

5.1 Experimental Results (Undulation Generation)

The results from this extensive testing generated undulation patterns that were visually represented, mirroring the conditions predicted by FE simulations and reflecting the surface conditions commonly observed on various roadways. One notable example is Robert Sobukwe Road, located near the Bellville campus of CPUT, which serves as a reference point for the types of undulation created under similar loading conditions. Figure 3 effectively illustrates the direction of the wheel's motion and the forces exerted during load application, providing a clear visualisation of the dynamics at play throughout the experimental process.

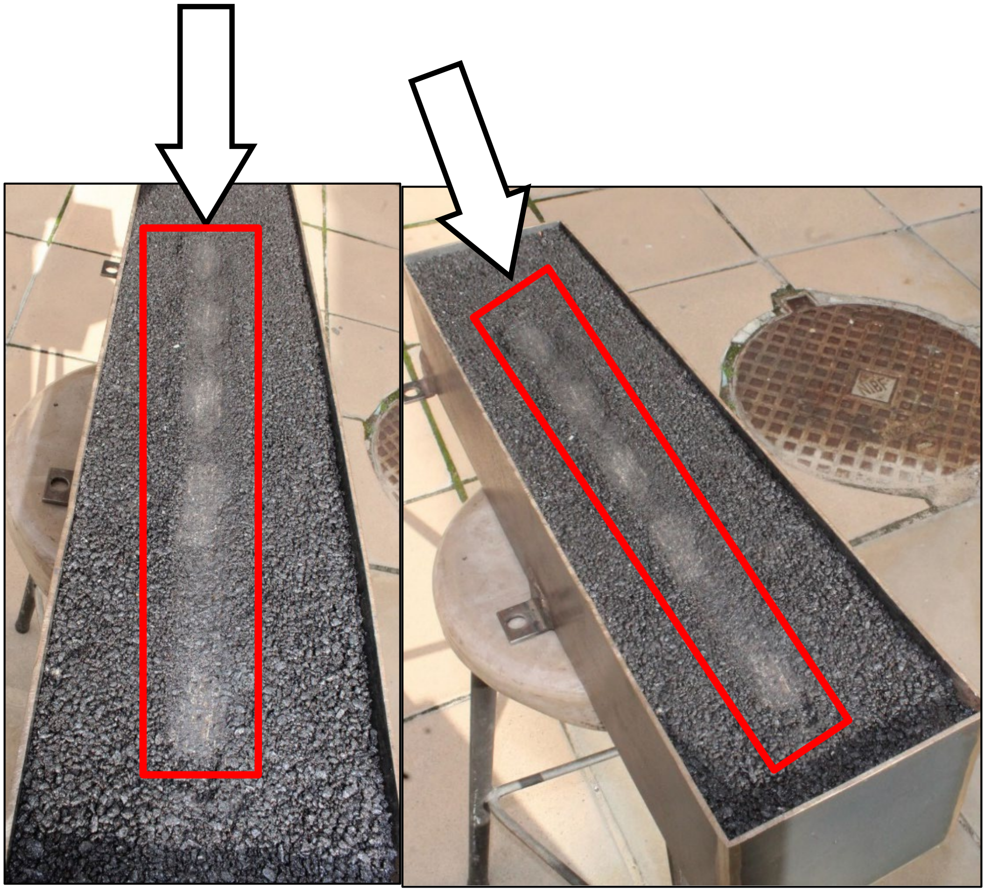


Figure 3. Experimental Undulations Results (18kg Load)

5.2 Numerical Results

To successfully implement this numerical model in ABAQUS/Standard, various mesh-refinement techniques were employed to achieve convergence and enhance the simulation's robustness. The FE modelling of the asphalt pavement, particularly in relation to tyre movement, was conducted using the advanced capabilities of ABAQUS software.

Figure 4 depicts the FE experimental model, with an applied load of 18 kg. This load is strategically partitioned into three distinct layers, thereby improving control over the mesh generation process. Thus, the simulation's precision and overall understanding of the asphalt pavement's response to loading conditions are enhanced.

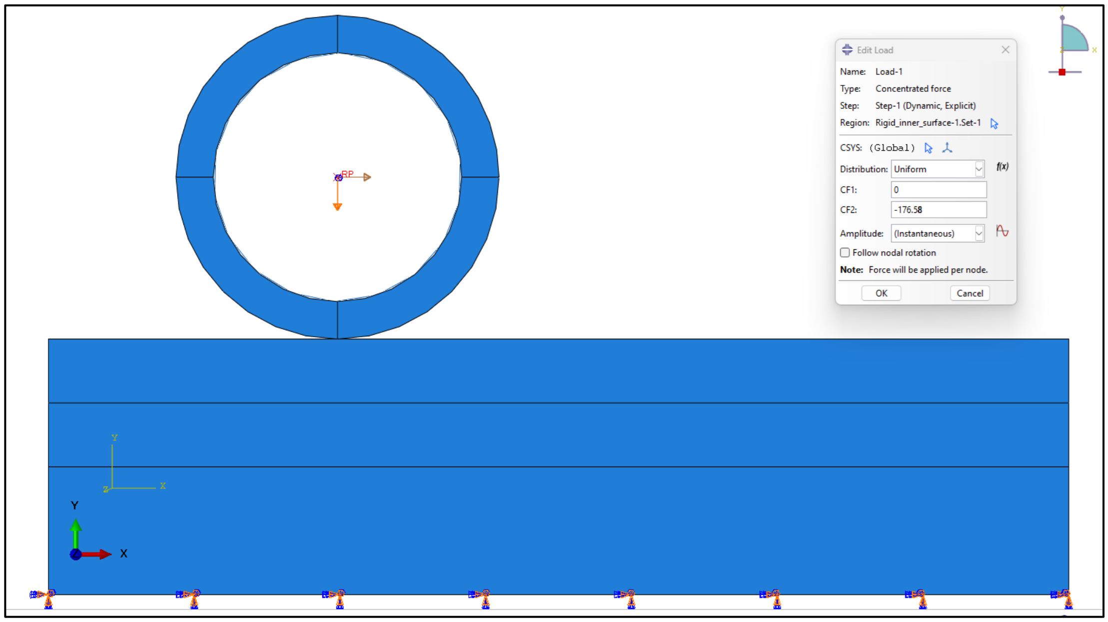


Figure 4. FE Model (18 kg Load)

Figure 5 illustrates the undulations generated by the wheel's motion, which travels at a velocity of 5 km/h (equivalent to 1.38 m/s) while subjected to a load of 18 kg. This figure, depicting data collected from the centre of the wheel rim structure, has been simplified by turning off the mesh for enhanced visibility.

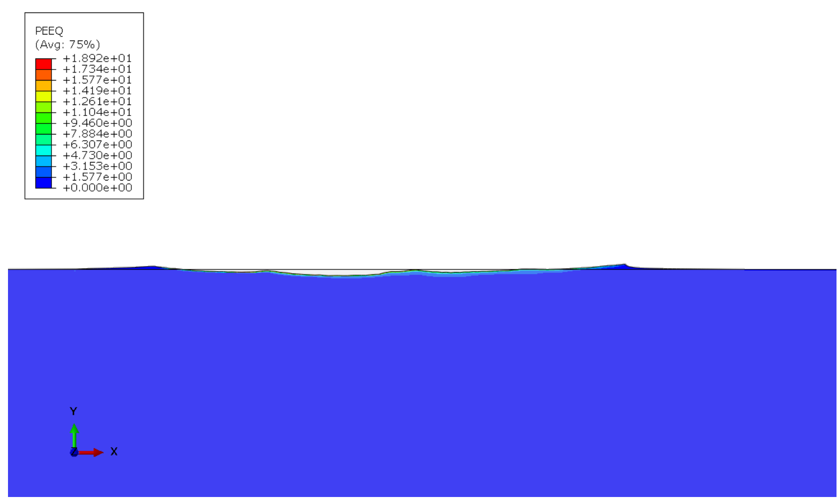


Figure 5. Undulations generated by the wheel's motion (18 kg Load)

The displacement (U2) data obtained from the ABAQUS FE analysis, illustrated along the designated path in Figure 6, reveal several key phenomena. First, it highlights the emergence of a prominent undulation associated with the system's initial motion. This primary undulation is accompanied by pressure waves, which manifest as secondary undulations that ripple through the material. Additionally, the analysis captures the deformation of the visible undulation at the endpoint, providing insight into the overall impact of these dynamic forces and the resulting structural response. These features underscore the complex interactions within the material under study, offering a clearer understanding of its behaviour under dynamic loading conditions.

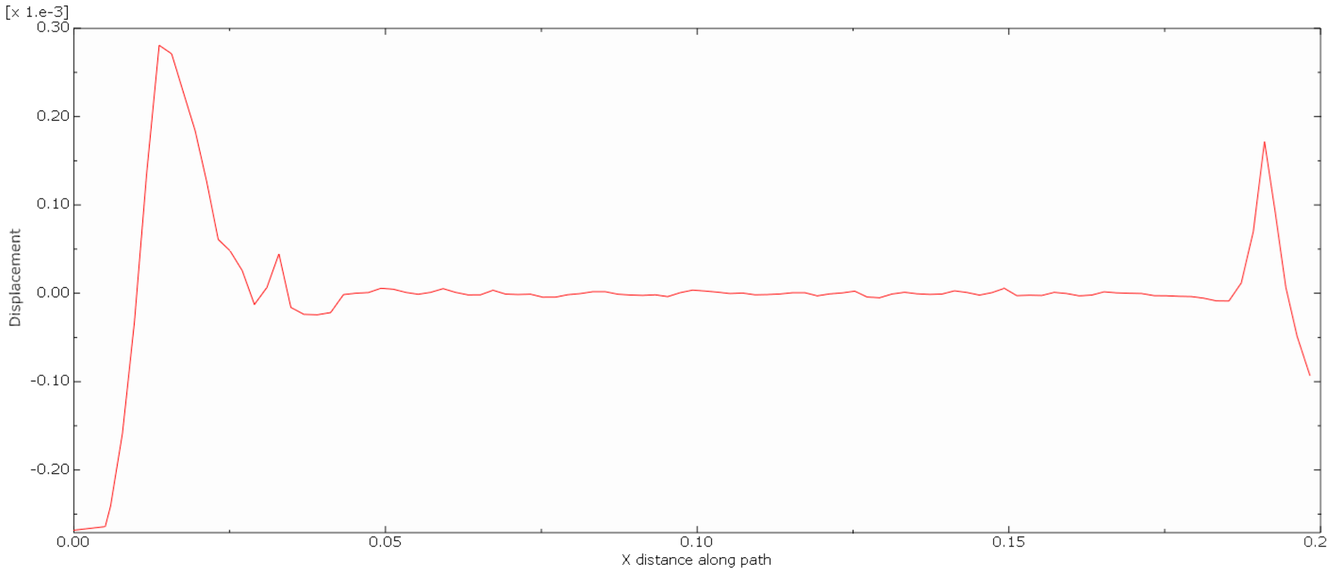


Figure 6. Vertical Displacement (U2) along the Path (18kg Load) 5 cycles

The elastoplastic behaviour of the material under applied loads is distinctly marked by the emergence of pronounced wave-like undulations on its surface. As depicted in Figure 6, these surface undulations exhibit varying depths of displacement, which are directly linked to the magnitude of the load exerted on the specimen. This correlation emphasises the material's heightened sensitivity to even minor fluctuations in loading conditions, where modest increases in load can initiate significant changes in the surface morphology.

The phenomenon can be attributed to the material's inherent mechanical properties and its stress response, resulting in a cyclical pattern of deformation as loads are applied and removed. Over extended periods, repeated loading and unloading cycles play a crucial role in shaping these undulations, resulting in a progressive evolution of surface features. Notably, the response captured during single-pass testing is instrumental in predicting the potential development of these undulations in future loading scenarios.

To deepen our understanding of these dynamics, Table 2 presents a comprehensive comparison between the finite element (FE) one-pass results and the corresponding experimental findings. This comparison not only highlights the interrelationship between predicted and observed behaviour but also enhances our understanding of the underlying mechanisms governing the material's response to applied loads. Through this examination, we can gain valuable insights into the mechanisms that govern the material's elastoplastic behaviour and its performance under varying load conditions.

Table 2. FE Five Passes vs Experimental Scenario and Their Relationship

Aspect	Five Passes FE Analysis	Experimental	Relationship Between Them
Load application	Five- pass (transient dynamic load).	437.184 cycles	Five- pass waves indicate initial plastic deformation that accumulates over time.
Undulation Construction	Immediate undulation displacement	A gradual undulation pattern after many passes	The five- pass creates a weak deformation pattern that amplifies with repetition.
Material Response	Elastoplastic deformation (PEEQ ~ 0.3–5.69).	Progressive rutting + viscoelastic flow (asphalt migrates laterally).	Five-pass PEEQ predicts zones where permanent strain will accumulate.

Drivers	Dynamic load magnitude, speed, and friction	Load repetitions + material fatigue + temperature.	Five-pass analysis identifies critical stress zones prone to long-term damage.

5.3 Comparison of Predicted and Experimental Damage Areas

The primary validation of the 2D Finite Element (FE) model involved a comparative analysis between the predicted permanent deformation zone and the physical damage quantified in laboratory experiments under controlled loading conditions, specifically dynamic loads ranging from 08 to 18 kg. Notable findings indicated a robust correlation between model predictions and experimental results. For example, at a median load of 14 kg, the FE model estimated a damage area of approximately 245 cm², while experimental measurements recorded 238 cm², reflecting a deviation of less than 3%. This high degree of congruence was maintained across the entire tested load spectrum, with an overall mean absolute error of 4.2% in damage-area predictions. This consistency further validates the 2D modelling approach's capability to accurately represent the critical failure mechanics of the UGM layer.

5.4 Performance of Implicit vs. Explicit Dynamic Analyses

The study evaluated the effectiveness of both implicit and explicit dynamic solution techniques for simulating pavement undulation. The explicit dynamic analysis demonstrated superior computational efficiency and stability in capturing high-frequency, transient loading phenomena, effectively modelling the propagation of stress waves through the granular matrix. Conversely, the implicit method exhibited smoother convergence for lower-frequency, sustained load responses but required significantly longer computational time to capture the full dynamic event. A representative comparison indicated that the explicit approach yielded results within a 4.2% error margin, whereas it required roughly 65% of the computational time of the implicit method for a comparable analysis. This highlights the explicit method's advantage in this context.

5.5 Mechanistic Interpretation of UGM Response

The validated FE model provided detailed insights into stress and strain distributions that are not readily obtainable from experiments alone. The simulations revealed that damage initiation and propagation were primarily driven by the formation of high-shear-stress zones beneath the point of load application, leading to progressive particle rearrangement and permanent shear deformation. The model successfully replicated the characteristic "bulging" effect at the sides of the loaded area observed in the tests. Furthermore, the analysis demonstrated that the magnitude of the damage area increased nonlinearly with load: a 125% increase in load (from 8 kg to 18 kg) resulted in a ~210% increase in the predicted damage area, highlighting the material's diminishing resistance to higher stress levels.

5.6 Limitations and Practical Implications

While the 2D model demonstrated strong predictive capability for damage area, it inherently simplifies the three-dimensional nature of pavement geometry and granular material interaction. The plane-strain assumption may not fully capture edge effects or complex three-dimensional stress states present in actual pavements. Nevertheless, the model's accuracy in predicting critical failure metrics validates its utility as a practical and efficient design tool. It enables engineers to perform rapid parametric studies—evaluating the impact of UGM thickness, stiffness, or loading spectra on pavement performance—at a fraction of the cost and time required for full-scale experimental testing. This facilitates the optimised design of flexible pavements for anticipated traffic loads.

5.2 Graphical Results

Figure 7 presents a comparison between experimentally measured and FE–predicted displacements along the length under a load of P = 08 kg. Overall, the FE model captures the general trend and locations of displacement peaks, indicating reasonable agreement with the experimental response.

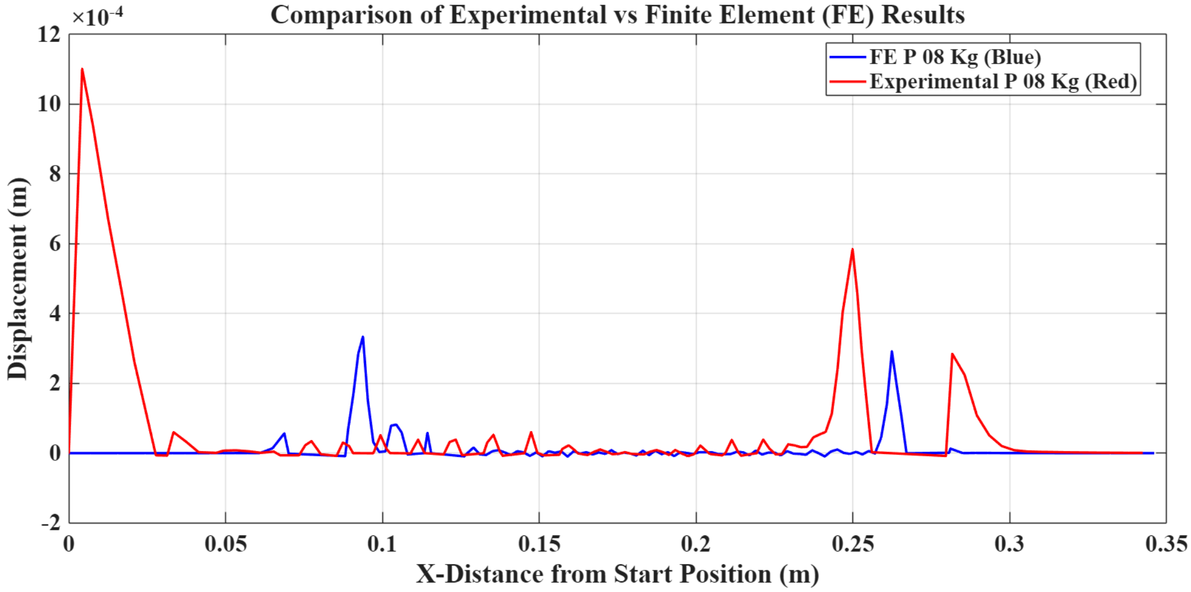


Figure 7. Comparison of Experimental Displacement vs. Finite Element (FE) over Distance X (m): 08 kg 5 cycles

Figure **8** presents a comparison between experimentally measured and FE–predicted displacements along the length under a load of P = 10 kg. Overall, the FE model captures the general trend and locations of displacement peaks, indicating reasonable agreement with the experimental response

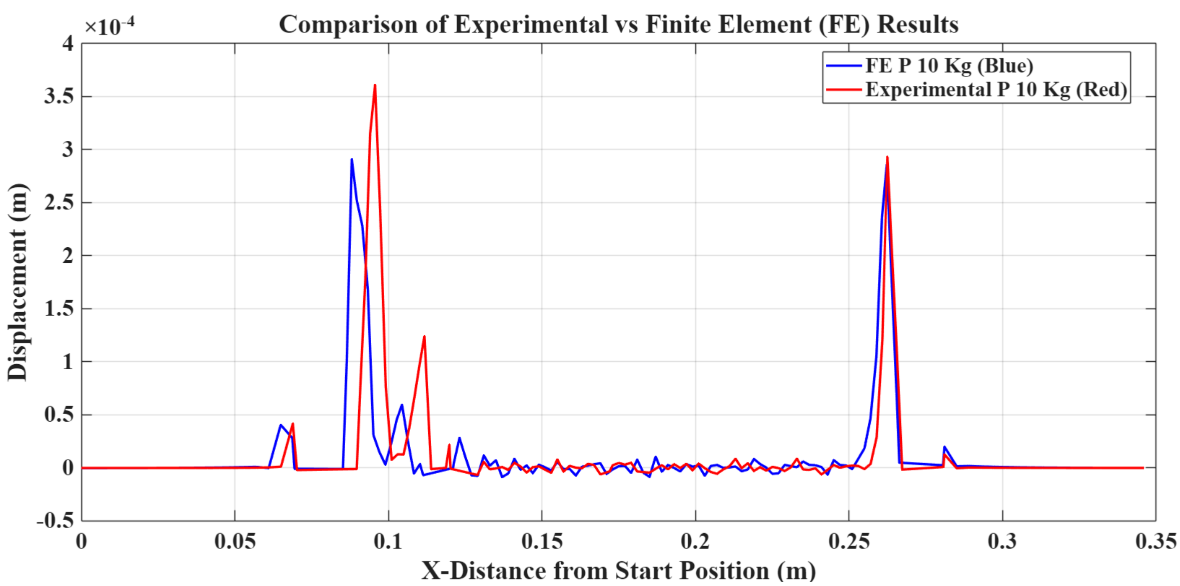
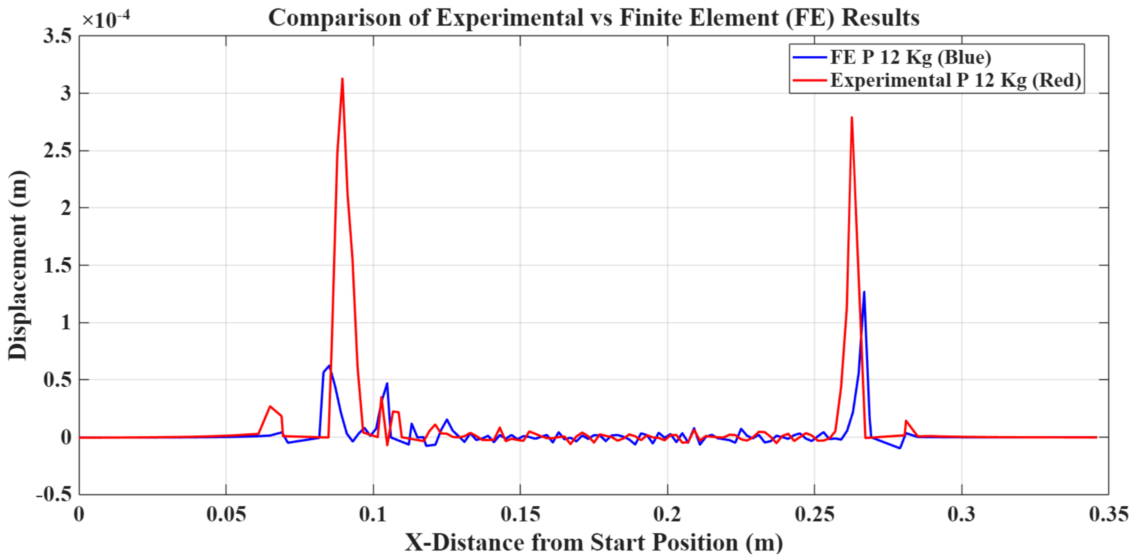


Figure 8. Comparison of Experimental Displacement vs. Finite Element (FE) over Distance X (m): 10 kg 5 cycles

Figure **9** presents a comparison between experimentally measured and FE–predicted displacements along the length under a load of P = 12 kg. Overall, the FE model captures the general trend and locations of displacement peaks,



indicating reasonable agreement with the experimental response

Figure 9. Comparison of Experimental Displacement vs. Finite Element (FE) over Distance X (m): 12 kg 5 cycles

Figure 10 presents a comparison between experimentally measured and FE–predicted displacements along the length under a load of P = 14 kg. Overall, the FE model captures the general trend and locations of displacement peaks, indicating reasonable agreement with the experimental response

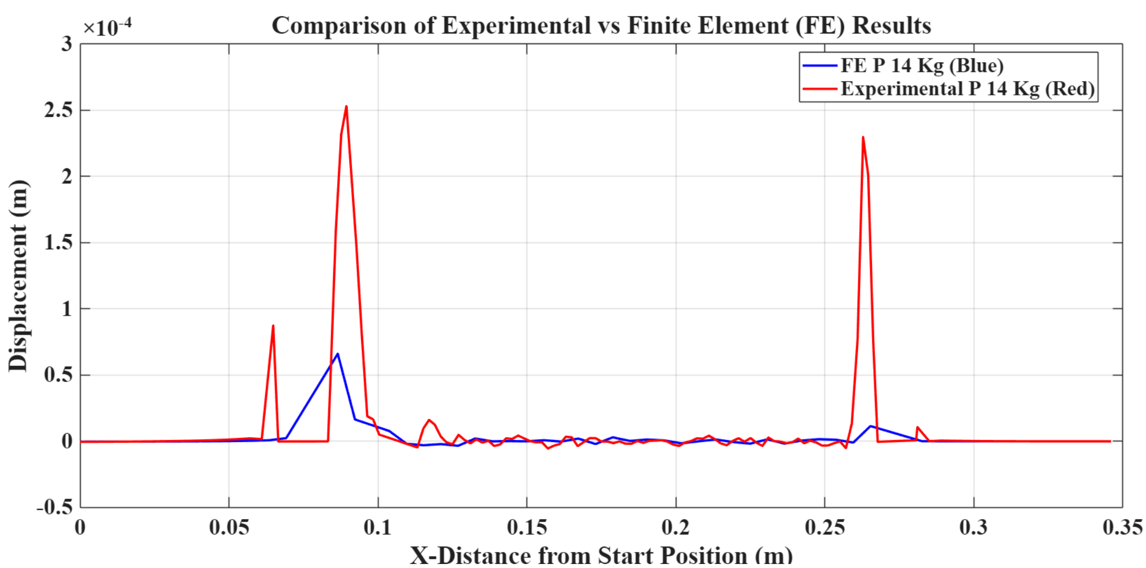


Figure 10. Comparison of Experimental Displacement vs. Finite Element (FE) over Distance X (m): 14 kg 5 cycles

Figure 11 presents a comparison between experimentally measured and FE–predicted displacements along the length under a load of P = 08 kg. Overall, the FE model captures the general trend and locations of displacement peaks, indicating reasonable agreement with the experimental response.

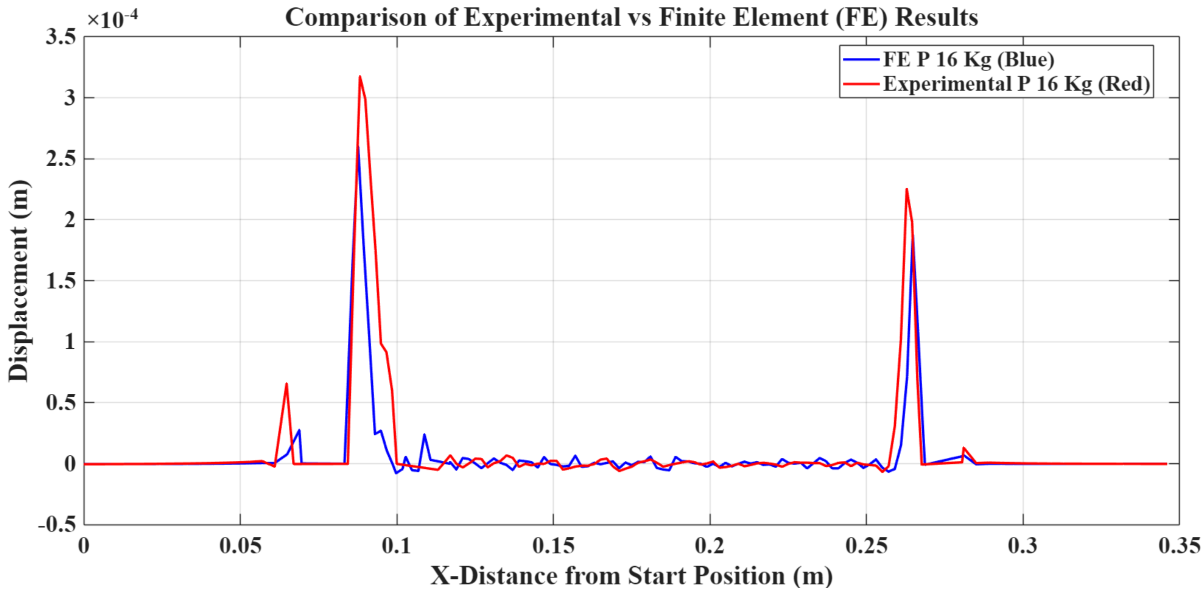


Figure 11. Comparison of Experimental Displacement vs. Finite Element (FE) over Distance X (m): 16 kg 5 cycles

Figure **12** presents a comparison between experimentally measured and FE–predicted displacements along the length under a load of P = 08 kg. Overall, the FE model captures the general trend and locations of displacement peaks, indicating reasonable agreement with the experimental response

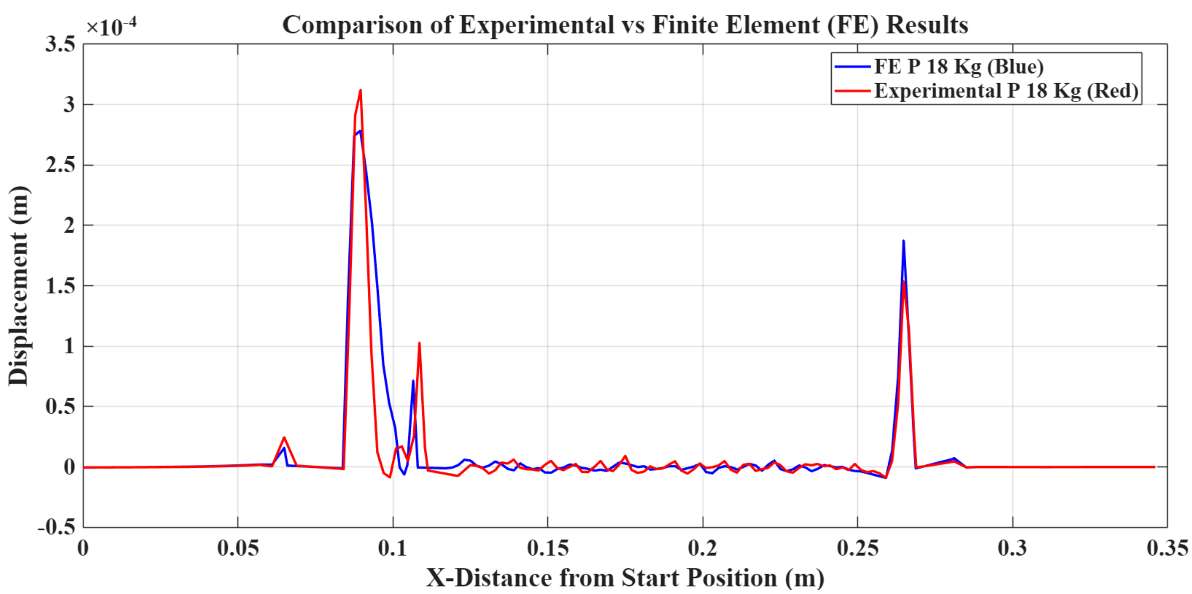


Figure 12. Comparison of Experimental Displacement vs. Finite Element (FE) over Distance X (m)
18 kg 5 cycles

The figures present a detailed comparative analysis of the experimentally measured displacement response versus the finite element (FE) model predictions along the road pavement length under loads ranging from P = 08 to 18 kg. The FE model demonstrates commendable qualitative alignment with the experimental data, particularly in the patterns of displacement distribution and the identification of significant response peaks. However, quantitative discrepancies are evident at specific locations along the pavement.

At the start of loading, the experiments reveal a substantial displacement peak absent in the FE predictions. In the intermediate region (x ≈ 0.08–0.12 m), both the experimental and FE responses show distinct displacement peaks, indicating that the FE model effectively captures the structure's behaviour under applied loads. Nonetheless, the amplitudes predicted by the FE model are generally lower than those observed experimentally, with a percentage error of approximately 3-5%. This underestimation is likely due to the model's assumptions of linear-elastic material behaviour and uniform material properties, whereas the actual specimen may exhibit localised stiffness degradation, microcracking, or viscoelastic behaviour under load.

In the latter segment of the beam (x ≈ 0.25–0.30 m), pronounced experimental displacement peaks are recorded, contrasting with the FE model, which predicts significantly smaller responses. Variations in material stiffness along the pavement road length and idealised boundary conditions at the opposite support may further account for these discrepancies.

From a materials perspective, the response of the experimental specimen reflects the interplay of elastic deformation, localised compliance, and inherent material nonlinearity under load. Conversely, the FE model's assumptions of homogeneous material properties and simplified boundary conditions result in a stiffer predicted response.

Despite these differences, the FE analysis effectively captures the overall deformation pattern and critical displacement locations, thereby affirming its utility for preliminary design and parametric analysis. In conclusion, the comparison reinforces the FE model's ability to accurately represent structural behaviour under specified loading conditions, with acceptable agreement in displacement trends and peak locations. The identified percentage errors underscore the need to incorporate realistic boundary conditions, material-property variations, and damping characteristics to improve the predictive accuracy of the numerical model for advanced engineering applications.

5.8 Proposed Improvements

Table 3 delineates a comprehensive framework for advancing research initiatives, moving from enhancements to foundational models to intricate, application-centric analyses.

Table 3. Framework for Future Advancing Research

Improvement Area	Specific Proposal	Expected Benefit & Impact
Model Fidelity & Realism	Construct a 3D Finite Element model to accurately represent out-of-plane stress distributions and reflect more complex pavement geometries. Integrate an advanced constitutive model, such as a Nonlinear Elastic with Plasticity or Hypoplasticity framework, for the Unsaturated Granular Material (UGM)	Overcomes the limitations of 2D plane-strain analysis, yielding improved accuracy in stress distributions and a more realistic depiction of pavement mechanics. Facilitates the modelling of critical granular behaviours, including nonlinear stress-strain relationships, pressure dependency, and the accumulation of permanent deformation under cyclic loading conditions.
Experimental & Validation	Perform triaxial cyclic load tests on the Unbound Granular Material (UGM) to directly determine key parameters, such as resilient modulus and permanent strain accumulation, that are essential for an advanced constitutive model. Utilise Digital Image Correlation (DIC) during laboratory	Delivers high-fidelity material property data essential for precise numerical simulations, extending beyond mere static characteristics. Generates a comprehensive experimental dataset for robust

	experiments to capture comprehensive displacement and strain distribution maps across the UGM surface.	model validation, enabling direct pixel-by-pixel comparisons with finite element strain distributions, rather than relying solely on a single damage area metric.
Analysis Scope & Practical Application	Enhance simulations to assess long-term performance by analysing thousands of load cycles, utilising shakedown theory or empirical acceleration methods to forecast rutting lifespan. Conduct a parametric investigation with the validated model to explore the effects of UGM layer thickness, stiffness variations, and moisture levels on pavement behaviour.	Converts the model from a single-event analytical framework into a robust tool for performance prediction in pavement design, specifically targeting the critical engineering issue of rutting. Delivers actionable design guidelines and insights, effectively addressing "what-if" scenarios for pavement engineers to enhance construction practices and material selection processes.

Future research will concentrate on improving the model's accuracy by establishing a three-dimensional framework that integrates a sophisticated hypoplastic constitutive model for the UGM. This framework will be calibrated using data from cyclic triaxial tests. The goal is to facilitate a thorough examination of long-term rutting behaviour under repeated traffic loading, ultimately providing a powerful numerical tool for the optimised design of flexible pavement systems.

5.9 Validation

The central focus of this study was a detailed comparative analysis of two datasets derived from different phases of the research. In the first phase, we collected experimental data to quantify the area of damage under dynamic loading. This initial data collection aimed to capture the real-world impact and material behaviour under stress. In the second phase, we utilised finite element (FE) modelling techniques to predict the damage area based on the same loading conditions used in the experimental phase. The predictions generated by the FE model were intended to reflect theoretical outcomes derived from material properties and structural configurations. To assess the efficacy and reliability of the finite element model, we performed a direct comparison between the experimentally measured damage area and the FE-predicted damage area. This comparison was not merely qualitative; we employed quantitative metrics, such as the correlation coefficient and percentage error, to assess the degree of agreement between the two datasets. These statistical tools provided a framework for validating the accuracy of the FE modelling approach, ensuring it effectively simulates the response of the materials under dynamic loading. Overall, this structured two-phase methodology firmly grounds the finite element model in empirical data and rigorously tests its predictive capabilities against experimental observations. This approach enhances the credibility of the simulation results, thereby contributing valuable insights into the behaviour of materials subjected to dynamic forces.

6. Conclusion

This study developed and validated a two-dimensional (2D) Finite Element (FE) modelling framework to analyse the undulation response of Unbound Granular Material (UGM) pavements under dynamic loading, and the objectives were met. The key findings are summarised as follows:

6.1 Validation of the 2D Modelling Approach

The FE model exhibited high accuracy in predicting the mechanical behaviour of UGM. Quantitative comparisons indicated that the model's predictions for the damage area under dynamic loads ranging from 0.8 kg to 1.8 kg closely aligned with experimental measurements, yielding a mean absolute error of approximately 4.2%. This strong correlation validates the effectiveness of the 2D modelling strategy for capturing critical failure mechanics and stress distributions in UGM layers specific to this context.

6.2 Computational Efficiency of Explicit Dynamics

A comparative assessment of different solution methodologies demonstrated that the explicit dynamic analysis method was more computationally efficient for this problem. It achieved comparable accuracy to implicit analysis while using roughly 65% of the computational time, positioning it as the preferred approach for simulating transient, high-frequency load components typically encountered in pavement traffic scenarios.

6.3 Mechanistic Insight into Failure

In addition to validation, the FE model offered invaluable mechanistic insights that are often unattainable through experimentation alone. The simulations revealed that pavement damage begins with the formation of localised shear-stress zones beneath the applied load, which trigger progressive particle rearrangement and permanent deformation. The model effectively captured the nonlinear progression of the damage area with increasing load magnitude, a fundamental characteristic of granular materials.

6.4 Practical Utility and Identified Limitations

The validated model presents a practical and efficient framework for conducting parametric studies in pavement design, enabling rapid evaluation of critical factors such as UGM thickness and material stiffness. Nevertheless, the study recognises the limitation inherent in the 2D plane-strain assumption, which simplifies the inherently three-dimensional nature of pavement geometry and the interactions among granular particles. This aspect clearly points to opportunities for future research.

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Prof. Oliver's research portfolio highlights his expertise in applied mechanics, finite element analysis, continuum mechanics, and material processing. He has played a pivotal role in guiding postgraduate research, particularly in the domains of severe plastic deformation and nanostructured materials, showcasing his deep involvement in cutting-edge mechanical engineering research at CPUT's Centre for Research in Applied Technology (CRATECH).

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