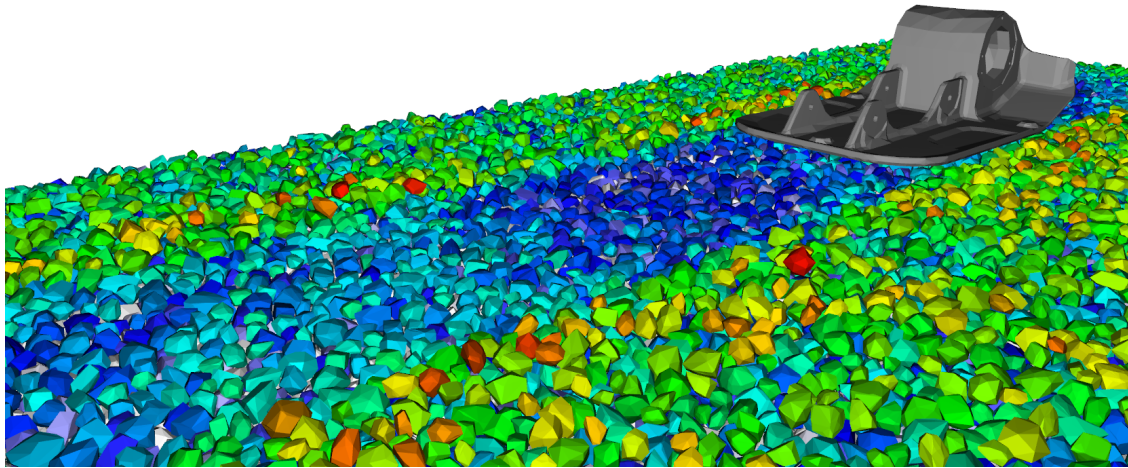




CHALMERS
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Discrete Element Method – Multi Body Dynamics Co-Simulation of a Vibrating Plate Compactor

Master's thesis in Mechanics and Maritime Sciences

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MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

MASTER'S THESIS 2026

A Discrete Element Method / Multi Body Dynamics Coupled Simulation for a Plate Compactor

Study of a Discrete Element Model of a Granular Substrate Coupled
With a Multi Body Dynamics Model of a Plate Compactor
Simulating a Compaction Operation

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Master's Thesis 2026

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Cover: Compaction Simulation of a Plate Compactor Operating on a 16 – 32 Particle Bed.

Typeset in L^AT_EX

Printed by Chalmers Reproservice

Gothenburg, Sweden 2026

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Abstract

Physical testing can be a time consuming process. It is therefore desirable to reduce the need for physical testing by simulating procedures using computer aided engineering. Challenges arise when systems span multiple disciplines, hindering full modelling using a single method. The interaction between a vibrating plate compactor and a gravel substrate is an example of this type of system. Often this issue is resolved through simplification, to fit the model to a simulation environment at the cost of reducing physical accuracy. This thesis instead addressed the issue by separating incompatible parts of the model into two simulations and coupling them through co-simulation. Co-simulation enabled individual models to run separately in their respective solvers while facilitating communication between them. The aim was to develop a co-simulation that coupled a Multi-Body Dynamics model of the vibrating plate compactor and a Discrete Element Method model of the gravel substrate. The full model was validated against physical tests to ascertain how closely the co-simulation replicated them. It was found that certain aspects of the physical tests were captured. New insights into how the machine-substrate interaction works, not possible to glean from physical testing alone were also found. The results show that these models can be useful to enhance and to a degree replace physical testing. Certain interesting phenomena from the experiments were captured by the final coupled model, with some results matching very well and others showing slight mismatches. Our conclusion is that the final model works well as a proof of concept. Thereby motivating coupling of Multi-Body Dynamics - Discrete Element Method simulations when evaluating the performance of vibrating plate compactors.

Keywords: Co-simulation, DEM, MBD, Plate Compactor, Granular Materials

Acknowledgements

We would like to express our appreciation and give thanks to our supervisor at Fraunhofer Chalmers Centre, Johannes Quist, for his valuable insights into coupled simulations between the discrete element method and multibody dynamics. You have continuously shown great engagement throughout this project by guiding us through the process of model construction and experiment execution. This opportunity has given us both valuable experience.

We would also like to give a huge thank you to our extra supervisor at Fraunhofer Chalmers Centre, Pontus Malmsköld. We would not have succeeded with this work without your constant support in programming, problem-solving expertise, and insightful discussions.

We want to express our thanks to Husqvarna Construction for initiating this master's thesis and giving us the opportunity to write it. A special thanks goes to Samuil Matev and Karl Elmestrand for continuous feedback and accommodating support throughout the project.

Finally, we want to show our gratitude to our examiner, Petri Piironen, who introduced us to this thesis and has been engaged since the beginning. We prize our meetings and will look back at those, and the entire project, with a smile.

This work has been initiated by Husqvarna Construction and carried out in collaboration with Fraunhofer Chalmers Centre.

Robin Cronheden, William Gustafsson, Gothenburg, May 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AI	Artificial Intelligence
API	Application Programming Interfaces
CAD	Computer-Aided Design
CAE	Computer-aided engineering
CoG	Center of Gravity
CoM	Center of Mass
Co-sim	Co-Simulation
DEM	Discrete Element Method
FFT	Fast Fourier transform
FMI	Functional Mock-up interface
FMU	Functional Mock-up unit
GPU	Graphics processing unit
HMD	Hertz-Mindlin-Deresiewicz (Contact model)
M1	+0/−32 mm gravel substrate
M2	+16/−32 mm gravel substrate
MBD	Multi-Body Dynamics
ODE	Ordinary Differential Equation
RVE	Reference volume element
UI	User interface

Nomenclature

Below is the nomenclature of indices, parameters, and variables that have been used throughout this thesis.

Indices

i, j	General indices used for enumeration, e.g. particles or time steps.
x, y, z	Indices denoting the spatial coordinate directions

Parameters

E	Young's modulus
G	Shear modulus
$\mathbf{I}$	Inertia tensor
m	Mass
dm	Mass Element
R	Smallest dilated radius
Δt	Time discretization step
ν	Poisson's ratio
ρ	Density

Variables

$\mathbf{F}$	Force vector
τ	Torque vector
d_e	Distance from the center of rotation to the center of mass
$\mathbf{q}$	Generalized coordinate vector
$\dot{\mathbf{q}}$	Time derivative of the generalized coordinate vector

$\ddot{\mathbf{q}}$	Second time derivative of the generalized coordinate vector
$\mathbf{r}$	Position vector
r	Perpendicular distance to rotation axis
$\mathbf{v}$	Velocity
quat	Quaternion
$\boldsymbol{\omega}$	Angular velocity
$\dot{\boldsymbol{\omega}}$	Angular acceleration
$\mathbf{Q}$	Generalized force vector
s	Travelled distance
P	Pressure
A	Area
$\mathbf{M}$	Mass matrix
$\mathbf{C}$	Damping matrix
$\mathbf{K}$	Stiffness matrix
Δt_c	Critical Time Step

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1

Introduction

Soil compaction is an essential step in achieving stable ground conditions in construction. It works by applying a cyclic periodic motion, where the compactor repeatedly hits the soil with a force that pushes the soil particles closer together. The purpose of compaction is to densify the ground and increase its stiffness before construction, so that the soil does not continue to settle under the load of the structure. However, the interaction between a compactor and the soil is complex, and several uncertainties remain regarding the behavior of the substrate and the resulting compaction level.

Studying this interaction often requires physical testing, which can be costly and time-consuming due to the need for planning, equipment, material, and physical test space. Computer-aided engineering (CAE) simulations can reduce this need by allowing the system to be studied in a more controlled and flexible environment. This can accelerate the research process, since different conditions can be tested more easily and measurements that are difficult to access experimentally can be extracted directly from the simulation.

This thesis investigates the problem by constructing a CAE-model of this interaction, with the aim of using it as a tool to simulate the soil compaction process while capturing the response of both the soil and the compactor.

1.1 Background & Motivation

The substrate contains voids between the particles, meaning that the particles can rearrange when an external load is applied. The overall density of a particle region can be described by the ratio between solid material and air voids. During compaction, the cyclic load from the compactor forces the particles to move closer together and rearrange into a denser structure. As the void ratio decreases, the particles obtain more contact points and interlock more strongly, which increases the stiffness of the substrate and makes the bed respond more like a connected structure.

The compactor studied in this project is a vibratory plate compactor. The periodic motion is generated by an eccentric shaft rotating at high speed, inducing excitation of the base plate. The base plate transfers kinetic energy to the substrate which re-

arranges the aggregate to fill voids, resulting in increased density. This densification process is what is referred to as compaction.

A critical step to modeling any system through simulation is selecting the appropriate tool for the task. Problems arise when multidisciplinary systems cannot be fully represented using a single computational method. Modeling a gravel bed consisting of thousands to hundreds of thousands of individual rocks interacting with a vibrating multi-body system is a perfect example of such a problem. In these situations, one part of the system is often simplified in order to make the model compatible with a single CAE software, potentially reducing the physical accuracy of the simulation in the process.

This thesis aims to address this problem by instead employing a co-simulation approach. Allowing for the incompatible parts of the system to be modeled individually in a more fitting environment that is then simulated in conjunction as a single, coupled simulation.

The plate compactor model is simulated using multi-body dynamics (MBD). Multi-body dynamics is a numerical method used to simulate systems of rigid bodies connected through joints, constraints, and bushings. The motion is calculated from the forces and constraints acting on the system, while the gravel substrate is modeled using the discrete element method (DEM). The Discrete element method is a numerical method that is used to simulate granular materials, where the substrate is represented by individual particles that can move and rotate due to contact interactions. These two models are coupled through the functional mock-up interface (FMI), which allows each model to be solved in its respective software while interacting with the other model.

The purpose of the coupled model is to run simulations that can generate data for specific responses in both the machine and the substrate. The generated data can also provide a more detailed description of the internal response of the gravel, which is difficult to measure directly in physical tests. The model should be flexible and adjustable, allowing different parts of the system to be studied under different conditions. For the simulated data to be of practical use, the coupled model must be well grounded in physical behaviour. This requires validation against physical test data, which also opens up the possibility of calibrating the model.

With a successfully calibrated model, a large number of simulation data sets can be generated to predict compaction results under different conditions and support the development of plate compactors. From a research perspective, co-simulation for this type of application is still a developing area. This work therefore shows one possible use of co-simulation for studying the interaction between a vibratory plate compactor and a gravel substrate. Since these simulations are computationally demanding, increasingly powerful computers open new possibilities for using detailed coupled simulations in future development work.



Figure 1.1: Husqvarna LF60i plate compactor. Image reproduced from Husqvarna Construction website [1].

1.2 Aim

The goal of this thesis is to develop and evaluate an MBD–DEM co-simulation model of the interaction between a plate compactor and a gravel substrate. The aim is not to optimize the soil compaction process, but to investigate whether the coupled model can simulate relevant responses of both the compactor and the substrate. The model is validated against physical experiment data by comparing acceleration, forward velocity, pressure response and bed displacement, in order to assess its potential as a tool for further studies of plate–substrate interaction.

1.3 Literature Review

Coupled simulations have the potential to give insight into compaction physics. This section presents previous research regarding factors affecting the compaction level, simulation approaches, and evaluation methods that have led up to this project.

Anjaneyappa et al. [2] investigated the compaction characteristics of light compaction equipment, including rollers and plate compactors. Their study showed that the achieved compaction generally increases with the number of passes, but that the increase becomes smaller after repeated passes. This indicates that the compaction process approaches a point of diminishing returns.

Wersäll [3] studied the frequency dependence of soil compaction using vibratory equipment. The study showed that both vibration frequency and force magnitude affect the compaction response. It was also concluded that no single dynamic quantity governs the degree of compaction alone. Instead, the compaction result depends on the combined response of the soil, the excitation, and the operating conditions.

Brzeziński [4] simulated plate compaction using a DEM-based model to study the effect of compactor frequency on compaction efficiency. The study shows that DEM is useful for modeling granular compaction because it can track particle motion, contact interactions, and changes in the internal structure of the material. The gravel particles were represented using multi-spheres consisting of up to three spheres, while the plate compactor was modeled as a simplified rigid body within the same DEM environment.

Göransson Axås [5] used a co-simulation approach combining DEM and MBD to simulate vibratory roller compaction. The work describes the process of particle modeling, machine modeling, simulation setup, and coupling between the two solvers. The validation of the coupled model also gives useful insight into compaction theory and dynamic machine–substrate interaction.

Malmsköld [6] also used DEM–MBD coupling, where railway ballast tamping was studied using an FMI framework. In that work, the ballast bed was modeled using DEM and the tamping machine was modeled using MBD, allowing the two models to interact in a coupled simulation. The approaches used in these studies provide useful background for this thesis, where a similar coupling concept is applied to a vibratory plate compactor and gravel substrate.

Several studies have investigated roller compaction and soil behaviour using numerical models, where DEM and MBD have been shown to be useful for studying the interaction between rigid bodies and granular materials. However, to the best of the author’s knowledge, no previous study has been found that applies an MBD–DEM co-simulation framework to a vibratory plate compactor operating on a gravel substrate. The coupled model developed in this thesis can therefore provide further insight into the interaction between plate compactors and granular substrates.

1.4 Limitations and Scope

The aim of this thesis is to develop a co-simulation model and evaluate its feasibility for studying plate–substrate interactions. The evaluation methods must also be established as part of the thesis work. To facilitate quantitative evaluation of the results the following research questions are formulated:

1. Can the machine-substrate interactions be accurately modeled using a MBD–DEM co-simulation approach?
2. What experimental methods can be used to evaluate the model?
3. Which measurable variables and interactions can be used to validate the model against experimental results?

The model is limited to one specific machine, the Husqvarna LF60i, shown in Figure 1.1, and one gravel size distribution. These limitations are adopted to narrow the scope of the project, since setting up the MBD and DEM models requires careful tuning of parameters before meaningful simulation results can be obtained. By limiting the project to one machine–substrate combination, a more thorough analysis can be performed. This is in line with the overall aim of the project, as it allows for a more detailed and refined model to be developed.

1.5 Software

The multi-body dynamics simulations in this project are performed in MSC Adams[®], originally developed as the Automated Dynamic Analysis of Mechanical Systems software. Adams is a multibody dynamics solution that provides advanced simulation capabilities for analysing, optimizing, and validating complex mechanical systems [7]. The software also allows results to be post-processed both visually and quantitatively, and supports connections to other software for co-simulation. The Adams tools used in this project are Adams View, Adams PostProcessor, and Adams Controls.

For the DEM simulations, the Industrial Path Solutions (IPS) DEM solver Demify[®] is used. Demify is a high-performance DEM solver developed at the Fraunhofer-Chalmers Centre and is designed for large-scale simulations of non-spherical particles using graphics processing unit (GPU) computing [8]. The solver is written in C++ and is used in this project through its Python API.

The coupling between the models is performed using the Functional Mock-up Interface (FMI) framework. FMI is a tool-independent standard for exchanging and coupling simulation models [9].

1.6 Usage of Artificial Intelligence

In this project, an artificial intelligence (AI) agent, ChatGPT by OpenAI [10], was used for the following purposes:

- Spell checking and grammar improvement
- Assistance with programming code structure, plotting, and logic in Python
- Assistance with report syntax in LaTeX

2

Theory

The details of plate compaction and soil compaction required for this project are described in this chapter. This follows from Section 1.1 and continues with the theoretical background of the numerical methods used in the model, including multi-body dynamics (MBD), the discrete element method (DEM), and the coupling method, the Functional Mock-up Interface (FMI).

2.1 Plate Compactors and Soil Compaction

Soil compaction equipment is used to increase the density and stiffness of granular materials before construction. Large roller compactors are commonly used for larger areas, while plate compactors are more suitable for smaller areas, edges, trenches, and locations where larger machines have limited access.

A plate compactor works through a combination of vibration frequency and impact force magnitude. Inside the compactor, a rotating shaft contains a mass that is offset from the center of rotation. The excitation force generated by an eccentric mass depends on the rotating mass, distance between center of mass, rotation, and angular velocity. For a rotating eccentric mass, the harmonic excitation force can be expressed as

$$F = m_e d_e \omega^2, \quad (2.1)$$

where m_e is the eccentric mass, d_e is the distance from the center of rotation to the center of mass, and ω is the angular velocity. The plate is designed with a specific geometry that, together with friction against the ground, allows the machine to move forward during operation. An illustration of the base plate and eccentric shaft's motion is shown in Figure 2.1.

During operation, the base plate transfers dynamic loads into the substrate. In a gravel substrate, these loads are transmitted through contact points between individual particles rather than as a uniform pressure field. The contact network changes continuously as particles rearrange, causing the force paths through the bed to vary during operation. This makes the pressure response local and dependent on the current particle arrangement.

In gravel, repeated loading can also lead to fracture and abrasion. Fracture occurs when high contact forces cause particles to crack or break, while abrasion is caused by repeated contact and sliding between particles. These effects can change the

particle shape and size distribution over time, which in turn affects how forces are transmitted through the gravel substrate.

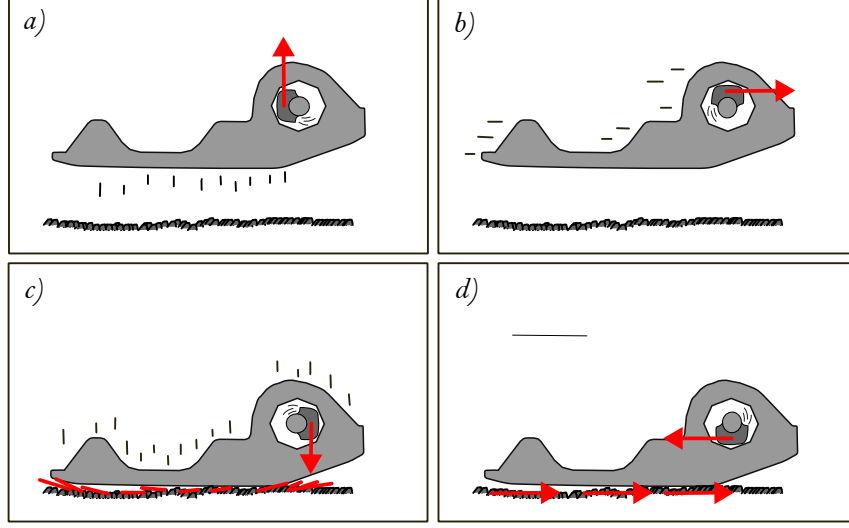


Figure 2.1: Illustration of the base plate motion during operation: (a) the eccentric shaft lifts the plate, (b) the shaft moves the plate forward, (c) the plate impacts the substrate, and (d) the shaft pulls the plate backward while the motion is resisted by friction.

2.2 Multi Body Dynamics

Multi-body Dynamics is a physic-based numerical method used to calculate the motion and interaction of connected rigid bodies. Each rigid body has six degrees of freedom, three translational and three rotational. When more than one rigid body is connected through joints such as springs, bushings, bearings, etc, the dynamics of the system change as the bodies now move with respect to each other. Each body has an equation of motion and through these joints a system of equations of motion (EoM) are constructed. Through Newton's second law of motion these EoMs can be solved for. The sum of forces in the system is set up as shown in equation (2.2).

$$m\ddot{\mathbf{r}} = \sum_j \mathbf{F}_j. \quad (2.2)$$

Here, m is the mass, $\mathbf{r}$ is the position vector, $\ddot{\mathbf{r}}$ is the acceleration, and $\mathbf{F}$ is the force vector.

The rotational equation of motion is written as

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega}) = \sum_j \boldsymbol{\tau}_j. \quad (2.3)$$

Here, $\mathbf{I}$ is the inertia tensor, $\boldsymbol{\omega}$ is the angular velocity vector, $\dot{\boldsymbol{\omega}}$ is the angular acceleration vector, and $\boldsymbol{\tau}$ is the torque vector. The cross product term describes the centrifugal contribution.

The equation of motion is set up in matrix form including damping and stiffness for the multi body dynamics system, see equation (2.4).

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}(\dot{\mathbf{q}}, \mathbf{q}) + \mathbf{K}(\dot{\mathbf{q}}, \mathbf{q}) = \mathbf{Q}. \quad (2.4)$$

Here, $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ is the damping matrix, $\mathbf{K}$ is the stiffness matrix, $\mathbf{q}$ is the coordinate vector, and $\mathbf{Q}$ is the generalized force vector.

Motion in an MBD system is governed by applied forces and torques, such as gravity, contact forces, impacts, and external excitation. In numerical MBD solvers, the continuous motion of the system is approximated by dividing the simulation time into discrete time steps. Starting from the initial positions and velocities of the bodies, the equations of motion are solved incrementally. At each time step, the solver updates the state of the system, including body positions, velocities, accelerations, and reaction forces or torques.

Multi-body systems connected by flexible elements, such as springs and dampers, exhibit natural frequencies at which they tend to vibrate when disturbed. In general, increasing the number of connected bodies tend to increase the number of natural frequencies in the system. If the system is excited at a frequency close to one of its natural frequencies resonance may occur, amplifying the dynamic response to levels that can damage system components.

2.3 Discrete Element Method

DEM is a physics-based numerical method with several similarities to MBD systems. Both methods are based on Newton's laws of motion, but DEM is suited towards modeling a comparatively large number of discrete particles. Motions, collisions and interactions are resolved for each particle individually. Although other numerical methods may be used to capture bulk behavior of granular materials, DEM allows for a more in depth view of the particle-particle interactions that cause the bulk phenomena.

A drawback of DEM is that it is computationally demanding. For every discrete particle, positions, velocities, accelerations and contact interactions are computed in each time step. Since DEM models can contain upwards of millions of particles, [11] computation time and space required to store simulation results can be a limiting factor. For each particle, the translational and rotational motions are calculated from its center of mass using Newton's second law of motion. This results in a system of ordinary differential equations (ODEs), which are solved numerically in time. The governing equations used for the DEM particles are given in equation 2.5.

$$m_i \frac{d\mathbf{v}_i}{dt} = \sum_j \underbrace{\mathbf{F}_{ij}^c}_{\text{contact forces}} + \underbrace{\mathbf{F}_i^g}_{\text{gravitational force}} \quad I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_j \mathbf{M}_{ij} \quad (2.5)$$

Here, $\mathbf{v}_i$ and $\boldsymbol{\omega}_i$ are the translational and angular velocities of particle i , respectively. The mass of particle i is denoted by m_i , while I_i is its moment of inertia and t is time.

The terms $\mathbf{F}_{ij}^c$ and $\mathbf{M}_{ij}$ represent the contact force and torque acting on particle i from particle j , or from contact with walls. The term $\mathbf{F}_i^g$ represents the gravitational force acting on particle i .

The particles are considered rigid bodies and cannot be deformed, meaning that two points on the body will always have the same distance between them. The contact force between particles is calculated using particle overlap. When overlap occurs, the overlap distance and relative velocities are used to determine the contact normal force from the Hertz-Mindlin-Deresiewicz (HMD) contact model [12]. This model represents the contact as a spring-damper system, as shown in Figure 2.2. The model can be adjusted using contact parameters, where the spring stiffness relates to the particle Young's modulus and the slider represents the friction in the contact. The damper acts as a "restitution" parameter, representing the amount of energy dissipated in the contact.

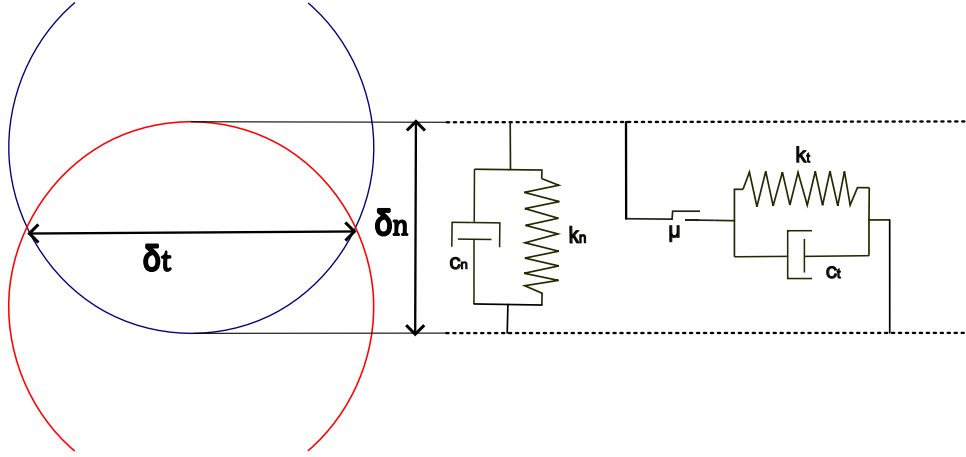


Figure 2.2: Schematic representation of the Hertz–Mindlin–Deresiewicz contact model, with normal stiffness and damping in the normal direction and tangential stiffness, damping, and a sliding friction limit in the tangential direction.

The HMD contact model is well-used in particle simulations. A limitation is that it refers to spherical particles. The simplest method to represent more complex shapes is to use dilated polyhedrons, where the shape is approximated using a cluster of small overlapping spheres. This technique retains the simplicity of spherical contact detection while enabling the construction of more complex particle shapes that better capture granular material behavior [13]. An illustration of this can be seen in Figure 2.3. A drawback is that the shapes created in this manner are required to be convex. As a result, any particle pair may only have one point of contact between them. There could be benefits to including concave particles as they allow for more contact points and contact-locking behavior. Creating such particles is, however, outside the scope of the thesis.

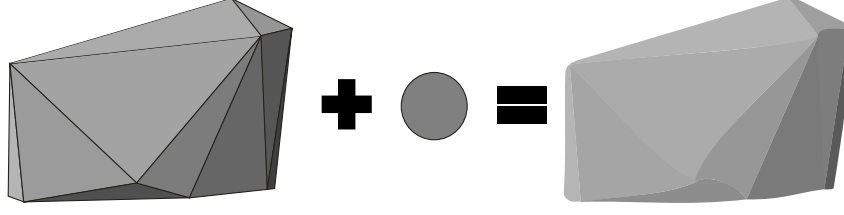


Figure 2.3: Illustration of a complex particle shape represented using a cluster of overlapping spheres.

Critical time steps for DEM simulations can be estimated using the Rayleigh Time Step Criterion. This approach is based on the propagation of Rayleigh waves through the particle assembly. Thornton and Randall showed that the Rayleigh wave speed can be used to estimate a stable critical timestep [14]. The Rayleigh time step can be written as:

$$\Delta t_c = \frac{\pi R \sqrt{\frac{\rho}{G}}}{0.8766 + 0.163\nu} \quad (2.6)$$

where R is the smallest particle radius, ρ is the density, G is the shear modulus, and ν is Poisson's ratio. In the case where dilated polyhedrons are used, R is taken as the smallest dilated radius, or characteristic size, of the particle. It is common practice to apply a large safety factor to the Rayleigh time step for DEM simulations [15]. To account for this, a reduction to 5 - 20% of the calculated Δt_c was performed to ensure numerical stability and accuracy.

2.4 Co-Simulation

Co-simulation is implemented using the Functional Mock-up Interface (FMI) standard. FMI was developed by the Modelica Association to simplify the creation, storage and exchange, of dynamic system models from different simulation environments [16]. In this project, co-simulation is performed using the FMI 2.0 framework, which enables general coupling between models by allowing each simulation environment to run independently while facilitating exchange of data at a defined communication interval. The results are likewise generated separately as output from each simulation.

Within the FMI 2.0 co-simulation framework, one simulation environment acts as the master while the second operates as the slave. The slave model is packaged as a functional mock-up unit (FMU), containing the complete model description in the form of a python script. The FMU is then imported into the master environment, allowing the master simulation to control the execution of the slave model. As a result, both simulations run in their respective environments while selected variables are exchanged at the defined communication interval. The communication interval is defined with respect to the simulation time of the coupled systems. The master algorithm advances the coupled simulation over this interval and ensures that variable exchange occurs at the specified communication points [17].

In this thesis, the Adams model acts as the master, while the Demify model operates as the slave. The coupling is achieved by packaging the Demify model as a FMU and importing it into Adams. The variables to be exchanged and the communication interval are specified within the Adams UI import interface. Once imported, the FMU functions as a black-box representation of the Demify model, with interaction limited to the interfaces defined by the FMI framework.

3

Numerical Methodology

This chapter documents the modeling methodology used in this thesis. Detailing the steps used for modeling the MBD model of the plate compactor, DEM model of the gravel substrate and how they are coupled in the FMI framework.

3.1 Multi-Body Dynamics Model

3.1.1 Model Simplification and Rigid Bodies

All MBD modeling was performed in Adams View, the Adams user interface (UI). The machine was modeled as a simplified representation made up by four main parts: the bottom plate, the frame, the battery plate, and the eccentric shaft. The part geometries were imported from a computer aided design (CAD) model of the machine. The component parts are shown in Figure 3.1.

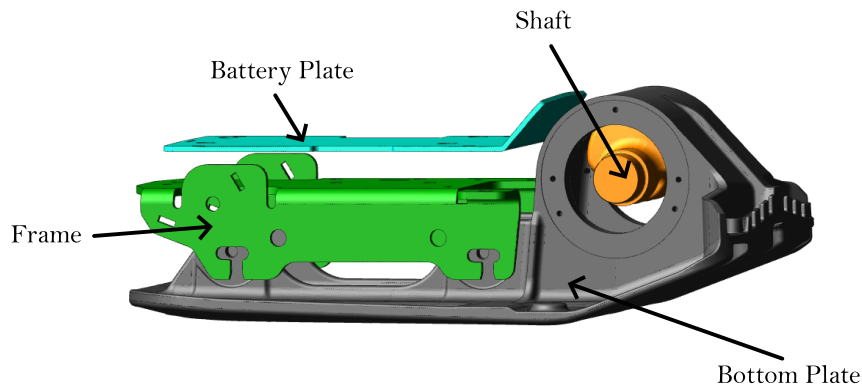


Figure 3.1: Simplified multi-body dynamics model of the plate compactor constructed in Adams View, including the bottom plate, frame, battery plate, and eccentric shaft.

The mass and center of gravity (CoG) of the four parts, as well as the mass and CoG of the full machine model were found through the CAD model. This allowed for manual setting of mass and CoGs in the Adams model, giving a simplified but

representative model of the full model. Some error is introduced in the inertia, I , properties since the exact mass distribution of the original geometry is not captured in the simplified model. The mass moment of inertia of a body is related to its mass distribution according to

$$I = \int r^2 dm, \quad (3.1)$$

where r is the perpendicular distance from each mass element dm to the considered rotation axis. Since the simplified geometry does not fully capture how the mass is distributed relative to these axes, the inertia properties may differ from those of the physical machine.

3.1.2 Connections and Excitation

The bottom plate, frame, and battery plate were connected using bushings. Different bushing properties were used for the connection between the bottom plate and frame, and for the connection between the frame and battery plate. This allowed the three main bodies to move relative to each other while still representing the compliance of the real machine.

The eccentric shaft was connected to the bottom plate using a cylindrical joint, allowing rotation only around its own axis. The excitation from the eccentric mass was represented by an imposed angular motion corresponding to the operating frequency,

$$\omega = 2\pi \cdot 95 \text{ rad/s}, \quad (3.2)$$

which gives a vibration frequency of 95 Hz.

An eigenfrequency study was conducted in Adams to indicate the eigenmodes of the system with the three relative bodies. This was carried out by mounting the model on a spring and letting it vibrate freely for two spring stiffness configurations. The most relevant results are presented in Table 3.1. The undamped natural frequency is calculated from the mass and stiffness of the system. Although damping affects the actual dynamic response, the undamped natural frequencies provide an indication of whether the operating frequency is close to one of the system's natural frequencies. It can be noted that the closest eigenfrequency to the operating frequency was below 28 Hz.

Table 3.1: Eigenfrequency study for two spring stiffness configurations.

E [MPa]	Mode	Undamped natural frequency [Hz]
500	23	13.95
500	24	21.80
500	25	27.67
500	26	25.77
500	27	759.15
50	23	13.93
50	24	21.78
50	25	27.68
50	26	25.74
50	27	240.46

3.1.3 Ground Contact Model

When the MBD model was run separately in Adams, the ground surface was represented by a box with a contact model. The contact parameters could be adjusted to match experimental data or to study how changes in the contact properties affected the motion of the plate compactor.

For example, the forward velocity was strongly affected by the friction coefficient and the stiffness of the surface. A higher friction coefficient generally increased the forward velocity, probably due to reduced sliding. A higher Young's modulus of the surface also tended to increase the forward velocity, although this relation was not strictly linear.

3.1.4 Path Stabilization

During operation, the plate compactor moved forward by itself. However, the model also showed accumulated lateral drift and yaw rotation. In physical testing, these effects are normally corrected by the operator.

To reduce this effect in the simulation, a torsional spring was added to limit the yaw rotation relative to the global axis. In addition, a spring-damper was added to reduce the lateral offset. These constraints had a negligible effect on the dynamics of the plate compactor but helped ensure that the model followed the intended path.

3.1.5 Interface to the DEM Model

The communication between the MBD and DEM models was performed using Adams Controls. To ensure correct variable exchange, matching reference points were defined at the bottom of the plate in both Demify and Adams, relative to each global coordinate system. These points were used as the reference locations from which the exchanged quantities were evaluated before being communicated through the FMI. In the Adams Controls interface, the input and output variables were then matched between Demify and Adams.

The force and torque received from the DEM model were applied to the bottom plate at the communication point. The FMU packaged from Demify was imported

into Adams, where the input and output variables were mapped. This resulted in a coupled system with a defined communication interval between the two solvers. Adams was used as the master solver, and the coupled model was run as a dynamic co-simulation.

3.2 Discrete Element Method Model

All models created in Demify were made using Python in order to script the models rather than build them using the UI. This was mainly because the FMI-methods were only compatible with the Demify Python methods. There are other benefits with scripting, such as more direct visibility of all settings and parameters used, automation through user defined functions and loops etc. Several different scripts and models went into creating the final model, these will be presented below together with an overview of how they work together to make the final model. The final model is shown in Figure 3.2. The particle bed has been rendered as semi-transparent to better show all component parts.

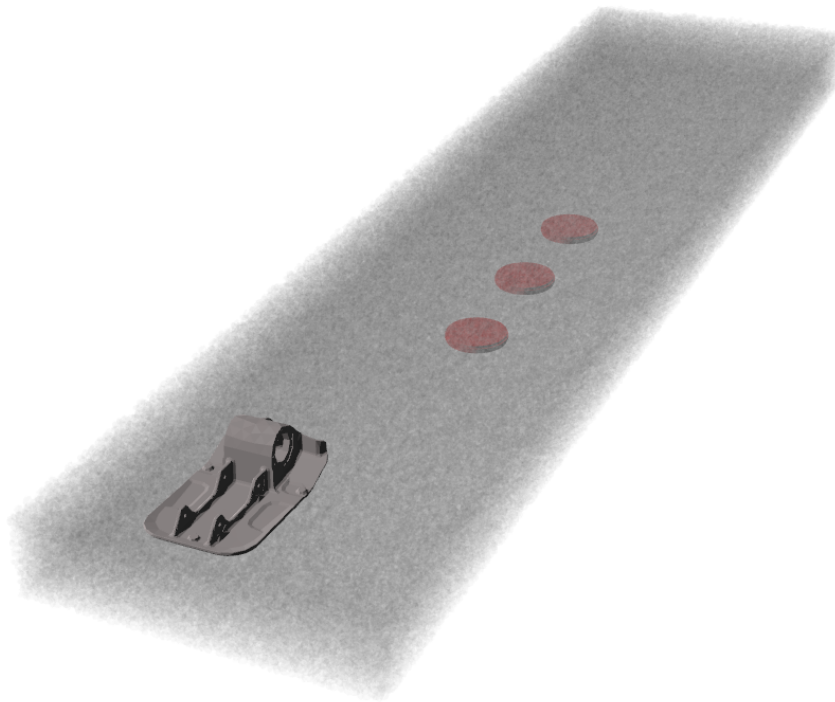


Figure 3.2: The final Demify model, with all component parts shown.

3.2.1 Particle Geometries

Particle geometries used in the gravel beds are defined through the particle models. Demify has a range of models to choose from, dilated polyhedron is the only model used in the thesis. The geometries used for the particles are a set of six 3D-scanned

rocks. When creating Demify particles, upper and lower bounds for the sizes of particles are selected, as well as a size distribution. For all simulations in this thesis, the particle size range was set to 16-32 millimeters, with a truncated normal distribution of sizes. During particle generation, every particle is assigned a size and a rock geometry. From a center point, the size defines a radius which is used to scale the particles so that the furthest edge of the rock is on the radius. In this manner the six rock geometries can be used to make a large variation of gravel with different sizes.

3.2.2 Reference Volume Element

There are several methods that can be used to create particles in Demify. The ones used in this project are particle generators and volume filling. A particle generator is a volume defined to spawn particles at a set rate. The generator will often be placed over another larger volume that will then be filled over time. This method works well when creating a simulated gravel bed as particles are allowed to fall freely into the larger volume to settle, resulting in a random distribution of particles in the bed volume.

The issue with this method is that it can be very time consuming to generate large amount of particles that have to fall into place, resulting in contact and bounces that have to be simulated. This was not a viable option for filling a full bed as the time to simulate the generation and settling of hundreds of thousands of particles would take up a large majority of the computation time.

An alternative is to use Demify's volume filling method, which allows for a snapshot of particles to be imported and projected over a desired volume. A script was created that enabled generating smaller volumes of particles for later export as snapshots. The particle volume generated by this script is referred to as a Reference Volume Element (RVE). The script allowed for setting particle geometries, material and contact parameters. The reference volume is made up of a box with the dimensions: length, width, height = $1.0\text{m} \times 1.0\text{m} \times 2.5\text{m}$, the extra 1.5 meters on the height being added to accommodate a $1.0\text{m} \times 1.0\text{m} \times 0.5\text{m}$ particle generator volume situated above the reference volume. When run, particles are generated until the box has been over-filled with particles. A destructor volume is then activated, culling all particles that overfill the box. The final result is a $1.0\text{m} \times 1.0\text{m} \times 1.0\text{m} = 1\text{m}^3$ RVE filled with settled particles, ready to be imported into any arbitrary volume. Three stages from the process of creating a RVE are shown in Figure 3.3.

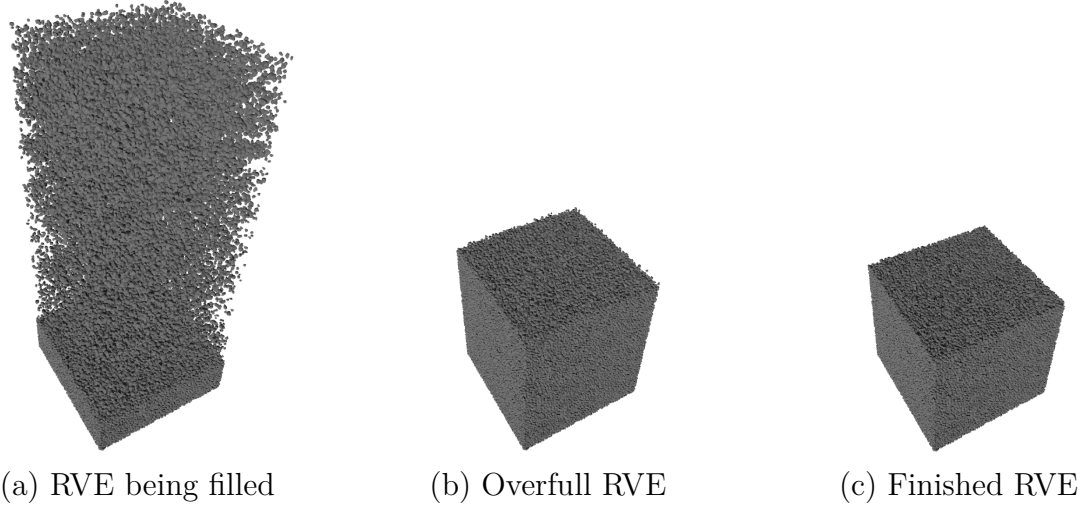


Figure 3.3: Three stages of RVE generation.

The script was also used to investigate the influence of particle contact friction on the initial packing density (initial referring to before compaction). Several RVEs were generated using different particle friction values, the packing density could then be measured over the volume. This enabled the relationship between particle friction and initial packing density to be evaluated.

3.2.3 Demify Model

The role of the Demify model was to handle the particle-plate interaction of the co-simulation. The model was defined as a Python script. The main components of the model are:

- The bottom plate from the machine, a rigid body with it's movements controlled by Adams through the FMU.
- A particle volume making up the bed, imported as a snapshot from either an initial bed, or the previous simulated passage.
- The domain enclosing the entire model, spans the particle volume plus additional height to accommodate the plate representation.
- Three rigid bodies representing of the pressure sensors. Geometries and dimensions made to match the actual Geokon sensors.

The script defines a bed filled with particles, initially imported from an RVE. The initial bed is run for 0.5 simulated seconds in a separate Demify instance. This is done because when importing RVEs that are smaller than the volume being filled, multiple RVEs are stacked with sides against each other. This resulted in voids where the sides of two RVEs meet. By allowing the bed to settle for 0.5 simulation seconds, the voids are reduced before the co-simulation is started.

At the bottom of the bed, rigid bodies representing the pressure sensors used in the experiments are placed, with their position determined by measurements taken from the 3D-scans of the empty experiment bed. The machine plate geometry is imported as a meshed part from a CAD model of the machine, which is then used

to define a rigid body for the plate.

The aim was to extract data from the Demify model in a manner comparable to the experiments, which required the model setup to closely resemble the experimental procedure. The dimensions of the experiment bed were set to length, width, height = 5.0m $\times$ 1.2m $\times$ 0.3m. The degree of compaction was measured using packing density ratios from before and after the pass, as well as an equivalent to a 3D-scan performed on the top layer of the particle bed to measure deformation. By measuring the force acting in the z-direction on the pressure sensor bodies, the pressure transmitted through the particle bed was calculated by dividing the measured forces by the surface area of the sensor body: $P = \frac{F_z}{A}$.

3.2.4 Demify Parameters

The parameters used for the Demify model were found through a mix of iteration, tabulated data and testing. Materials used in the experiment are defined as material objects in the simulation script. Any rigid body, particle or domain requires a material to be assigned to it. Three parameters define a material object:

- Density (ρ)
- Young's Modulus (E)
- Poissons Ratio (ν)

Three material models were used in the simulations, their parameters are presented in Table 3.2. The physical materials intended to be replicated for each object was: Particles: granite, plate: Steel, domain: Concrete.

Table 3.2: Material parameters used in Demify.

Parameter	Particles	Plate	Domain	Unit
ρ	2700	7800	2500	kg/m ³
E	20	40	28	GPa
ν	0.27	0.3	0.2	—

Note that the young's modulus is lower than what might be expected for such materials. A common method used to expedite DEM simulations is to lower the young's modulus, resulting in smaller contact overlap and allowing for larger time steps.[18]. For the same reason, the Plate's young's modulus was reduced based on observations in tests that it produced reasonable results. The Rayleigh time step shows that reducing the particles young's modulus from a more physically correct value of ≈ 60 GPa to 20 Gpa results in an increase of the upper limit for the critical time step from $\Delta t_c * 0.2 \approx 4.4 * 10^{-7}$ to $\Delta t_c * 0.2 \approx 7.7 * 10^{-7}$ when accounting for the reduction to 20% of the calculated Rayleigh time step. The lower recommended limit for the time step is 5% of the critical time step, resulting in a range of possible time steps for a young's modulus of 20GPa:

$$1.9 * 10^{-7} < \Delta t < 7.7 * 10^{-7}.$$

A time step of $\Delta t = 5.0 * 10^{-7}$ s was selected for the DEM simulations to balance computational cost and numerical stability.

Contact interactions in the model were defined using the Demify HMD contact object. Each contact object specifies the interaction between two material objects and must be defined for contact forces to be resolved between them. The contact model includes two user-defined parameters:

- Coefficient of Friction.
- Coefficient of Restitution.

Because these parameters strongly influence both plate propulsion and particle-particle contact dynamics, two of the main phenomena used to validate simulations, they were frequently calibrated during model testing. The final values set for these parameters are show in Table 3.3.

Table 3.3: Contact parameters used in Demify.

Parameter	Particle-Particle	Plate-Particle	Domain-Particle	Unit
Friction	0.7	0.9	0.7	—
Restitution	0.4	0.3	0.2	—

3.3 Co-Simulation

This section will outline the co-sim method. A detailed overview of the workflow as well as component parts from each individual model will be presented together with the relevant parameters. An illustration of the co-simulation in action is shown in Figure 3.4. The picture shows a time step from a coupled simulation where the plate has just impacted the particle bed. Particles have been rendered semi-transparent with a filter highlighting moving particles.

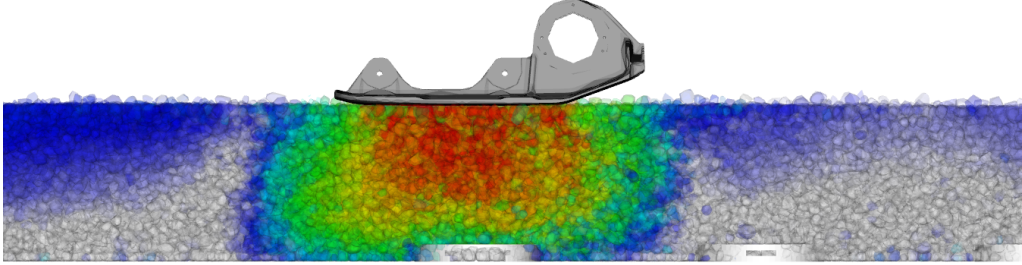


Figure 3.4: Co-simulation model illustration of the operating compactor, with particles colored by their velocity. Redder colors indicate higher particle velocities.

3.3.1 Co-Simulation Overview

In the co-simulation setup, the Demify simulation is configured as the slave system to the Adams master simulation. The coupling process begins by packaging the desired Demify model as a Functional Mock-up Unit (FMU) for import into Adams. The FMU is generated using a built-in Demify export function that follows the FMI 2.0 framework. As part of the export process, input and output variables for the FMU are set, defining which variables to synchronize in each communication interval. The FMU is then imported into the Adams model through the Adams View UI import interface. Within Adams the corresponding variables are mapped to the ones defined in the FMU. The communication interval used for synchronization between the simulations is also specified during import. Once the variable mapping and communication settings have been defined, the co-simulation is executed by running the Adams simulation in the standard manner.

A schematic overview of the co-simulation algorithm, as defined through the FMI and Adams interfaces, is presented in Figure 3.5. The sequence of operations is read left to right, and is additionally color coded for clarity.

1. (Red) The master (Adams solver) requests the FMI to advance the simulation time to the next communication step t_{i+1} .
2. (Blue) Through the FMI, the solvers are instructed to simulate until the requested simulation time is reached in both solvers.
3. (Green) Once both solvers have simulated to the requested time, the dynamic and kinematic quantities are synchronized through the FMI in preparation for the next step.

3.3.2 Communication Interval

It was decided that matching the synchronization with the time steps of the Adams model would be the best approach. The only requirement for the communication

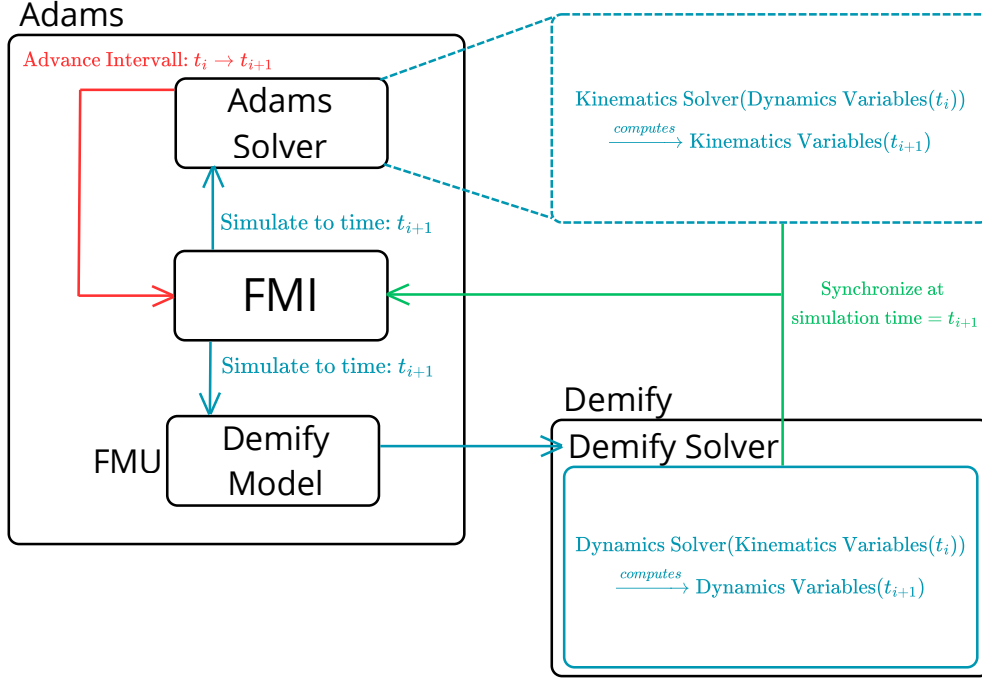


Figure 3.5: Schematic view of co-simulation procedure.

time step was to capture the 95Hz vibration of the plate, for which a time step of $\Delta t = 10^{-4}$ would be adequate. The performance impact was analyzed through testing. It was found that increasing the communication interval step to $\Delta t = 10^{-3}$ had negligible effects on computation time. With no drawbacks stemming from this finer communication interval, it was decided to set it to $\Delta t = 10^{-4}$.

3.3.3 Co-Simulation Implementation

To mimic the physical testing procedure, the machine was simulated running over the same substrate for ten consecutive passes, with one individual simulation performed for each pass. This removed the need for resetting the plate to the starting position for each pass. Since Adams enforces physical constraints during simulation, implementing a reset would have required a non-trivial method to lift and reposition the plate. Data handling was simplified as results from each run could be stored and post-processed individually. With comparatively shorter simulations, the impacts from errors was reduced and could be addressed between passes. A challenge introduced by this approach was how to carry over changes from the last simulation to the FMU. Since the FMU effectively acted as a black box containing a specific Demify model, restarting the simulation reset the bed to the initial state defined in the model. To allow for repeated passes over the same bed, a snapshot of the bed was saved after each pass. The snapshot from the latest pass was then imported into the same Demify model, which was repackaged into a new FMU. This new FMU replaced the previously imported FMU in Adams before the next simulation run.

3.3.4 Co-Simulation Variables

The bottom plate of the machine was the primary component of interest in the co-simulation. All variables exchanged in the coupling were related to the plate's kinematic and dynamic states. The variables used in the coupling are listed in Table 3.4. During the FMU import stage in Adams, all exchanged variables had to be explicitly defined to make them available in the Adams user interface. Although Demify can track dynamic quantities, it lacks the capability to resolve the resulting kinematic response. Adams, on the other hand, is specifically designed to handle dynamic and kinematic interactions. As such, the primary outputs communicated from Demify to Adams were the contact forces and torques acting on the bottom plate due to interaction with the gravel. These loads were applied at the mesh center of the plate in Adams, where they were used to compute the next time step. The updated kinematic quantities were then communicated back to Demify in the form of translational positions, rotational orientations, velocities, and angular velocities of the mesh center.

Table 3.4: Variables computed in each solver.

Software	Variables	
Demify	Forces	(F_x, F_y, F_z)
	Torques	(τ_x, τ_y, τ_z)
Adams	Positions	$(\text{Pos}_x, \text{Pos}_y, \text{Pos}_z)$
	Quaternions	$(\text{Quat}_w, \text{Quat}_x, \text{Quat}_y, \text{Quat}_z)$
	Velocities	(V_x, V_y, V_z)
	Angular Velocities	(W_x, W_y, W_z)

4

Experimental Methodology

One objective of this project was to simulate the contact interaction between the plate compactor and the substrate. For the coupled model to be useful, it had to be grounded in physical measurements. Experimental data was therefore collected to calibrate the plate compactor model and to validate the coupled MBD–DEM model against physical behaviour.

Two experiments were conducted. The first experiment focused on the plate compactor itself and was used to calibrate the MBD model. The second experiment included both the plate compactor and granular substrates and was used to validate the coupled model against experimental data.

4.1 Calibration Experiment

4.1.1 Purpose

The plate compactor calibration experiment was conducted to collect data on the dynamic behaviour of the machine. The purpose was to provide experimental data for calibration of the MBD model before introducing the interaction with a granular substrate. The experiment focused on the relative motion between the main bodies of the compactor, the free vibration response of the plate, and the forward velocity of the machine.

4.1.2 Experiment setup

The experiment was performed on a rubber mat placed on a concrete floor. The rubber mat had known properties and was used to create a controlled contact condition between the plate and the ground. Accelerometers were mounted at two measuring points on the machine to measure the dynamic response during operation, as in Figure 4.1. The signals were recorded using Brüel & Kjær accelerometers connected to a Brüel & Kjær LAN-XI Type 3050-A-060 data acquisition module. A known distance was marked on the rubber mat to enable measurement of the compactor travel time using stopwatches. In addition, a synchronized multi-view camera system consisting of Sony RX0 cameras was set up to record the test.



Figure 4.1: Accelerometers mounted on the bottom plate and the frame of the plate compactor.

To complement the ground-supported measurements, the plate was suspended freely from the frame and operated while hanging, as in Figure 4.2. This setup allowed the vibration response of the plate to be measured without direct influence from the ground contact.



Figure 4.2: Plate compactor suspended in the frame.

4.1.3 Measurement procedure

For the ground-supported measurements, the relative acceleration between the main bodies of the compactor was measured in different configurations. Three repeated runs were performed for each configuration to ensure consistency of the measured data.

For the free-hanging configuration, the plate was operated while suspended from the frame. This measurement was used to study the acceleration amplitude of the plate under isolated operating conditions.

The forward velocity of the compactor was measured separately. The machine was driven five times over a known distance on the same rubber mat surface, and the travel time was measured using stopwatches. During the initial part of each run, the machine was held back for approximately one second to allow the vibration and forward motion to stabilise. The average velocity was then calculated from the measured travel time after this start-up phase.



Figure 4.3: Photo of one of the passes in the calibration experiment.

4.1.4 Data collection

The experiment provided acceleration data from the plate compactor, including relative acceleration between the main bodies and acceleration amplitudes from the free-hanging plate configuration. The experiment also provided an estimate of the average forward velocity of the machine. These data were used to calibrate and evaluate the MBD model of the plate compactor. A summary is presented in Table 4.1.

Table 4.1: Summary of measured data in the plate compactor calibration experiment.

Measured	Quantity	Equipment
Plate compactor main bodies	Relative acceleration $[m/s^2]$	Accelerometers
Bottom plate, free-hanging	Acceleration amplitude $[m/s^2]$	Accelerometers
Compactor bottom plate	Forward velocity $[m/s]$	Stopwatches and known travel distance

4.2 Validation Experiment

This section includes the process of the validation experiment. A page from a testing approach document regarding this coupled experiment is found in Appendix A.

4.2.1 Purpose

The compactor–substrate validation experiment was conducted to collect data on the interaction between the plate compactor and granular substrates. The purpose was to validate the coupled MBD–DEM model using experimental data from both the machine and the substrate. In contrast to the calibration experiment, where the compactor was operated on a controlled surface, this experiment was performed under more realistic operating conditions.

Two granular materials were tested: makadam +0/-32 and makadam +16/-32, where +0/-32 and +16/-32 refer to the approximate particle size ranges in millimetres. The +0/-32 material is more commonly used in construction applications and was included in the physical testing to provide an additional experimental comparison. However, since the focus of the thesis is model validation, the +16/-32 material was selected for the coupled model validation because its coarser particle size distribution is more suitable for DEM simulation.

4.2.2 Experimental setup

The experiment was performed in an excavated test strip of approximately $10\text{ m} \times 1.2\text{ m} \times 0.3\text{ m}$. The test strip was divided into two sections, one for each granular material. The plate compactor was operated along the centerline of the bed.

Three Geokon Model 3515 granular material pressure cells were used to measure the ground pressure response in the substrate bed [19]. The sensors were placed along the centre line at the bottom of the bed, with a spacing of 0.5 m between

them. The pressure signals were recorded using a DEWESoft KRYPTON data acquisition system.

The experiment included measurements of both the compactor response and the substrate response. Accelerometers were mounted on the plate compactors bottom plate to measure the machine dynamics during operation. The signals were recorded using Brüel & Kjær accelerometers connected to a Brüel & Kjær LAN-XI Type 3050-A-060 data acquisition module [20].

In addition, dynamic stiffness measurements were performed using a ZORN ZFG 3000 GPS light weight deflectometer [21]. These measurements provided an additional estimate of the substrate stiffness.

The surface geometry of the substrate was measured using a FARO 3D Focus3D S20 [22] laser scanner. Reference spheres were placed around the test area and used as reference points for point-cloud matching between repeated scans. This allowed the surface geometry to be measured after each pass and later compared to evaluate the deformation of the substrate surface.

To record the experiment and enable measurement of the forward velocity, synchronized Sony RX0 cameras [23] were set up to provide a multi-view overview of the experiment.

4.2.3 Test-bed preparation

Before the beds were filled with substrate, the bottom of the excavated strip was compacted using a plate compactor. This was done to reduce the influence of the underlying layer on the measured response and to increase its stiffness. A geotextile fabric was then placed in the bed, and the pressure sensors were positioned on top of it. An initial 3D scan was performed to obtain the geometry of the empty bed.

The material was weighed before and after filling the bed, which made it possible to estimate the initial density of the substrate. The same preparation procedure were used for both granular materials. A comparison of the empty and filled test bed, both from the experiment and from the point cloud, is shown in Figure 4.4 and 4.5.

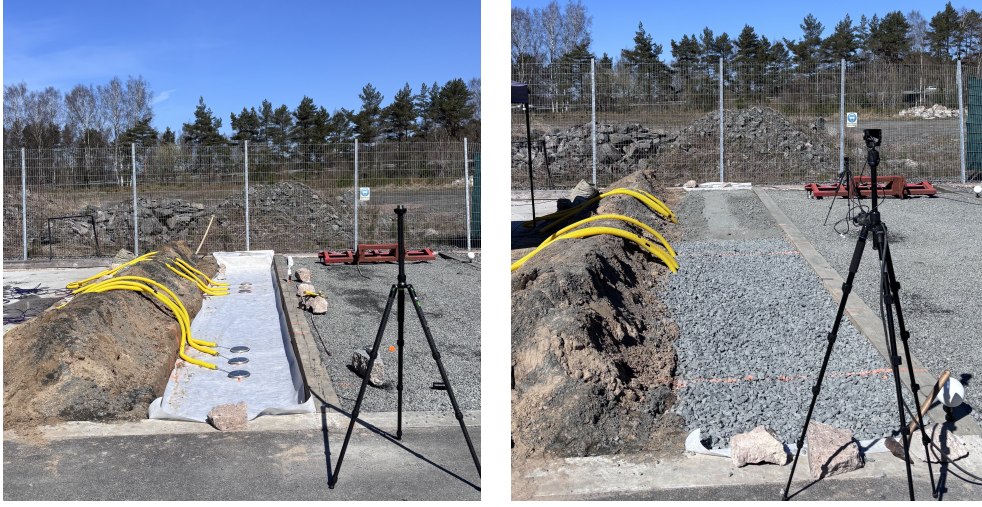


Figure 4.4: Photographs of the empty and filled test bed.

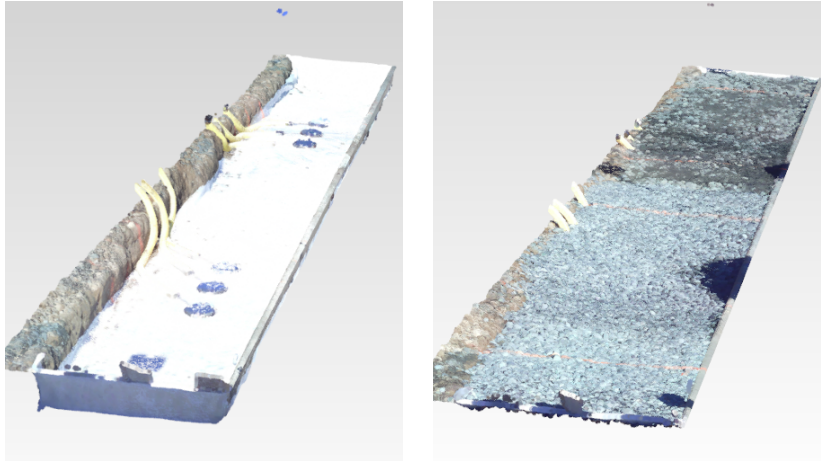


Figure 4.5: Point clouds of the empty and filled test bed.

4.2.4 Measurement procedure

After the bed preparation, the accelerometers were mounted on the machine and the cameras were positioned. The plate compactor was then operated for ten consecutive passes along the centreline of the bed. After each pass, the compactor was lifted back to the starting position and another pass was performed in the same direction. For the forward velocity measurements, the machine was initially held back for approximately one second to allow the compactor to reach a stable operating condition before travelling freely along the test bed.

The surface geometry was measured using a 3D scanner after each pass. This made it possible to study how the surface changed with increasing number of passes. Deflectometer measurements were also performed, but at a separate location from the area used for 3D scanning. This was done because the deflectometer requires several

impacts to estimate the dynamic stiffness, which could affect the local compaction level. Separating the deflectometer location from the scanned area reduced the risk of disturbing the compaction-level measurements. The same procedure was repeated for both granular materials.



(a) View 1.



(b) View 2.



(c) View 3.

Figure 4.6: Synchronized Sony RX0 camera views of pass 3 on the 16–32 material.

4.2.5 Data collection

The experiment provided acceleration data from the plate compactor, pressure data from the bottom of the substrate bed, forward velocity data, surface geometry data from 3D scanning, and dynamic stiffness estimates from the deflectometer. Together, these measurements were used to evaluate the coupled model by comparing both the machine response and the substrate response against experimental data. A summary is presented in Table 4.2. Experimental data comparisons for vertical surface displacement and deflectometer values for the two materials are presented in Appendix A, in Figures C.1 and C.2.

Table 4.2: Summary of measured data in the compactor–substrate validation experiment.

Measured	Quantity	Equipment
Plate compactor bodies	Acceleration [m/s^2]	Accelerometers
Bottom of substrate bed	Pressure [Pa]	Pressure sensors
Plate compactor motion	Forward velocity [m/s]	Synchronized cameras
Substrate surface	Surface geometry [m]	3D scanner
Granular substrate	Dynamic stiffness [MPa]	Deflectometer
Granular material	Mass [kg]	Scale
Empty and filled test bed	Volume [m^3] / geometry	3D scanner

4.3 Validation Simulation

This section describes how the validation experiment was represented in the coupled simulation. The simulation focuses on validating by comparing experiment and simulation results for the -16/+32 gravel test case.

4.3.1 Purpose and approach

To validate the coupled model against the compactor–substrate experiment, the simulation setup was designed to resemble the physical experiment as closely as possible. The aim was to reproduce both the operating conditions of the plate compactor and the initial state of the granular bed, so that the simulation results could be compared directly with the experimental data.

The simulation setup included the same number of passes as the physical experiment, corresponding measurement locations on the plate compactor, pressure sensor representations at the bottom of the bed, and surface geometry measurements after each pass. In this way, the coupled model was evaluated using comparable quantities from both the machine and the substrate.

4.3.2 Initial bed generation

The initial particle bed was generated to match the initial state of the physical test bed. The bed volume was obtained from the 3D scan of the empty physical bed,

while the amount of material added to the bed was determined from the measured material mass. These quantities were used to estimate the packing density of the physical substrate.

The solid rock volume, V_{rock} , was calculated as

$$V_{rock} = \frac{m_{rock}}{\rho_{rock}}, \quad (4.1)$$

where m_{rock} is the measured mass of the added material and ρ_{rock} is the assumed rock density. The void volume, V_{air} , was then calculated as

$$V_{air} = V_{bed} - V_{rock}, \quad (4.2)$$

where V_{bed} is the total bed volume from the 3D scan. The packing density was defined as

$$\phi = \frac{V_{rock}}{V_{bed}}. \quad (4.3)$$

Based on this estimate, the physical bed was found to consist of approximately 69 % solid rock volume. An RVE with a matching packing density was therefore selected for the initial simulation bed. As shown in Figure 4.7, the RVE generated with an initial friction coefficient of 0.2 resulted in a packing density close to 0.70. This RVE was therefore used to fill the simulation bed volume and generate the initial particle bed. The contact friction used during this process was only applied as a numerical method to achieve the desired initial bulk volume. A more accurate contact friction value was used in the coupled simulations.

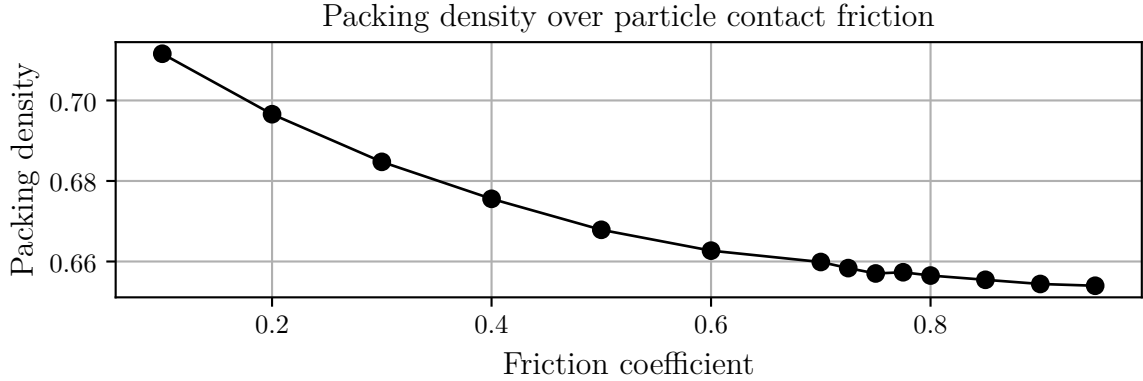
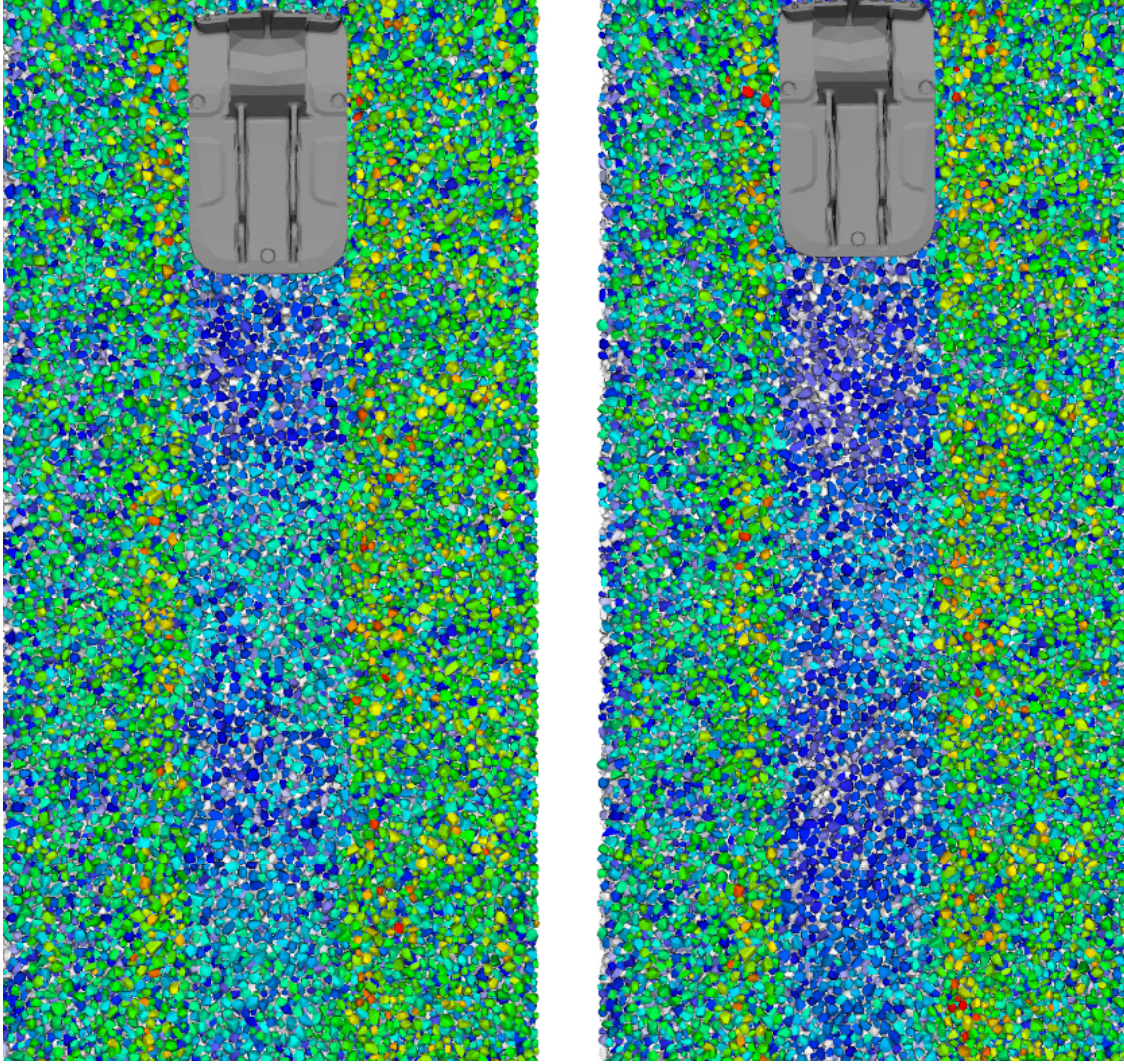


Figure 4.7: Study of initial bed packing density on a RVE over particle friction.

4.3.3 Repeated pass procedure

The simulation was divided into ten consecutive passes, corresponding to the ten passes performed in the physical experiment. After each pass, the final state of the particle bed was saved and used as the initial state for the following pass. This made it possible to include the accumulated change in the substrate between consecutive passes.

The plate compactor was repositioned to the starting position before each new pass, in the same way as in the physical experiment. Each pass was then simulated in the same direction along the centreline of the particle bed. Screenshots from pass 2 and 4 is displayed in Figure 4.8



(a) Pass 2.

(b) Pass 4.

Figure 4.8: Simulation top view of Pass 2 and Pass 4, with particles colored according to their vertical coordinate. Lighter green colors represent the upper layer, while blue colors represent particles deeper in the bed.

4.3.4 Simulation measurements

Measurement points were defined in Adams at positions corresponding to the accelerometer locations on the physical machine. These points were used to extract acceleration data from the MBD model in the same way as in the experiment.

The forward velocity of the compactor was also extracted in Adams using a measurement point on the bottom plate. To make the velocity estimate comparable to

the physical experiment, the average velocity was calculated after the initial start-up phase.

Rigid bodies representing the pressure sensors were placed at the bottom of the particle bed. Their positions were based on measurements from the 3D scan of the physical bed. These bodies were used to measure the force transmitted through the particle bed in Demify.

To reproduce the surface measurements from the physical experiment, a virtual 3D scan of the particle bed was performed after each simulated pass. The surface geometry was extracted and saved for comparison with the corresponding 3D scans from the experiment. A summary of the compared data is presented in Table 4.3

Table 4.3: Summary of experimental measurements represented in the coupled simulation.

Experiment	Simulation	Comparison
Accelerometers on the plate compactor	Adams measurement points at corresponding locations	Acceleration response of the machine
Forward velocity from camera measurements	Adams measurement point on the bottom plate	Average forward velocity after start-up phase
Pressure sensors at the bottom of the bed	Rigid sensor bodies placed at corresponding positions in Demify	Force/pressure response through the particle bed
3D scan of the substrate surface after each pass	Virtual 3D scan of the particle bed after each pass	Surface geometry and compaction development
Initial bed volume and material mass	RVE-based particle bed with matching packing density	Initial substrate state before compaction

4.4 Data Processing

This section describes how the experimental and simulation data were processed before comparison. The validation data consisted of acceleration signals, pressure signals, forward velocity measurements, and point cloud data from the substrate surface. Each data type required separate post-processing to allow comparison between experiment and simulation.

Acceleration data were used in two stages. First, acceleration measurements from the plate compactor calibration experiment were used to calibrate and evaluate the dynamic response of the MBD model. Second, acceleration measurements from the

compactor–substrate validation experiment were used to validate the coupled MBD–DEM model under operating conditions on granular material.

Pressure data were used to compare the force transmission through the substrate bed, while forward velocity measurements were used to verify the operating speed of the compactor. Point cloud data were used to evaluate the surface displacement of the substrate after consecutive passes.

The following sections describe the processing and interpretation of each data type.

4.4.1 MBD model calibration

Acceleration data from the plate compactor calibration experiment were used to calibrate the dynamic response of the MBD model. The calibration focused on matching the acceleration amplitude of the bottom plate between experiment and simulation. The bushings, introduced in Section 3.1.2, were used to represent the spring–damper connections between the main parts of the plate compactor. The bushing stiffness was defined separately in the normal and shear directions, while the damping was represented by a single damping value. The bushing parameters between the bottom plate and the frame were adjusted from the initial values until the simulated acceleration amplitude matched the experimental data reasonably well. The initial parameter values were based on new bushing properties. However, since all validation data were obtained from the same machine, the model needed to represent the worn bushings rather than a new set.

The second bushing pair, between the frame and the battery plate, was modeled using material parameters for the rubber material. These bushings were not calibrated, since calibrating the coupled motion of three relative bodies through two bushing pairs was considered outside the scope of the project. The manufacturer-provided bushing properties were therefore used as an approximation to capture the main dynamic behaviour.

The centre of mass for the three relative bodies was calibrated by studying the forward velocity of the plate compactor. The balance of the compactor was adjusted until the simulated forward speed compared well with the experimental data. The forward velocity was chosen as a calibration quantity since the forward motion is influenced by the centre of mass, the bushing properties, and the excitation from the eccentric shaft. Therefore, matching the forward velocity indicates that the overall dynamics of the MBD model is captured reasonably well.

4.4.2 Acceleration signal processing

Acceleration signals from both experiments and simulations were processed in Python before comparison. The signals were then compared in both the time domain and the frequency domain.

The frequency content was studied using a fast Fourier transform, FFT, where the acceleration signal was transformed from the time domain to the frequency domain.

This was used to identify the operating frequency of the compactor and to compare the frequency response between experiment and simulation. The FFT was implemented using the NumPy library in Python [24].

For visual comparison in the time domain, the acceleration signals were plotted over shorter time intervals. The simulation signals was also phase-shifted relative to the experimental signal to make the amplitude comparison clearer. This phase shift was only used for visual comparison and does not change the acceleration values or the frequency amplitudes.

4.4.3 Forward velocity processing

The experimental forward velocity was calculated from the measured travel time over a known distance,

$$v_{\text{avg}} = \frac{s}{t}, \quad (4.4)$$

where s is the travelled distance and t is the measured time.

In the simulation, the forward velocity was extracted for each timestep from an Adams measurement point on the bottom plate. The average velocity was calculated as the mean value after the first second, excluding the start-up phase where the compactor was allowed to stabilise.

4.4.4 Pressure signal processing

Pressure data was used to compare the substrate response between experiment and simulation. In the simulation, only the vertical force acting on the sensor bodies could be extracted. To approximate the pressure, p , this force was divided by the sensor area according to

$$p = \frac{F_z}{A}, \quad (4.5)$$

where F_z is the vertical force and A is the sensor area.

Both the experimental and simulation pressure signals contained initial pressure offsets. These offsets were removed by subtracting the initial value of each signal. The resting bed was therefore set to 0 Pa, and the remaining pressure variation was interpreted as the response caused by the plate compactor.

The experimental and simulation pressure signals also had a time offset. To allow for visual comparison, the signals were aligned using the pressure peaks as reference points, since the peak response occurs approximately when the compactor passes above the sensors.

The experimental pressure sensors sampled at 2000 Hz, while the simulation output was saved at 400 Hz. To compare the signals at similar sampling intervals, every fifth value of the experimental data was used, giving an effective sampling frequency of 400 Hz. Since the compactor operated at approximately 95 Hz, the reduced sampling frequency corresponds to about four samples per vibration cycle. Short-duration pressure peaks may therefore be missed, especially in the simulation output. For this reason, the pressure magnitude for each pass was evaluated using

the 99.9% percentile value instead of the absolute maximum. This reduced the influence of isolated peaks while still representing the upper pressure response during the pass. The pressure peak comparison should therefore be interpreted as an approximate comparison of pressure magnitude, rather than an exact comparison of individual peak values.

The pressure signals were also analysed in the frequency domain using the same FFT approach as for the acceleration signals. This allowed comparison of the dominant pressure response between experiment and simulation, as well as comparison between the plate motion and the pressure response at the bottom of the bed. “

4.4.5 Point cloud processing

Point cloud data were used to evaluate the surface displacement of the substrate after each pass. Each point cloud consisted of global coordinate points describing the scanned surface of the bed. Before processing, a rectangular region covering the travelled path of the plate compactor was selected.

The selected region was divided into several slices along the travel direction. For each slice, the average vertical coordinate was calculated. The slice averages were then averaged to obtain one representative surface height for each pass.

The vertical displacement was calculated by comparing the surface height after each pass with the initial surface height. This provided an estimate of the surface compaction, which could be compared between the experimental scans and the virtual 3D scans from the simulation.

4.5 Calibration & Verification

The experimental data collected in Section 4.1 were used to calibrate and verify the isolated MBD model. The calibration included adjustment of the bushing parameters between the bottom plate and the frame, as well as adjustment of the center of mass of the main bodies. The results are evaluated by comparing the simulated and measured acceleration response, the dominant frequency in the FFT, and the forward velocity of the plate compactor.

The results from the calibration of the bushings between the bottom plate and the frame are shown using an acceleration comparison of the bottom plate mounted free-hanging in the frame. The calibration resulted in a good agreement in acceleration magnitude. The results are displayed in Figure 4.9.

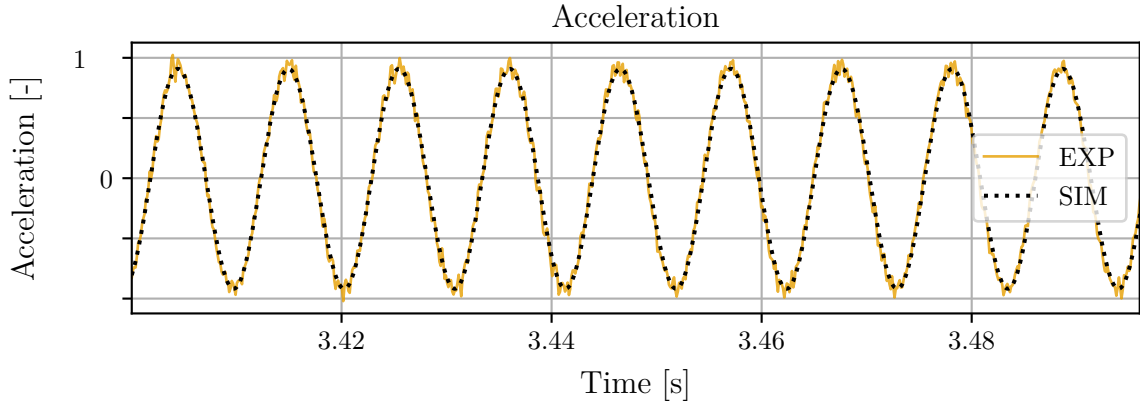


Figure 4.9: Free-hanging plate test mounted in frame: zoomed and phase-shifted acceleration. (Normalized)

The frequency response is presented both over the full frequency range and in a zoomed view in Figures 4.10. The results show that the MBD model captures the operating frequency of 95 Hz in the bottom plate acceleration.

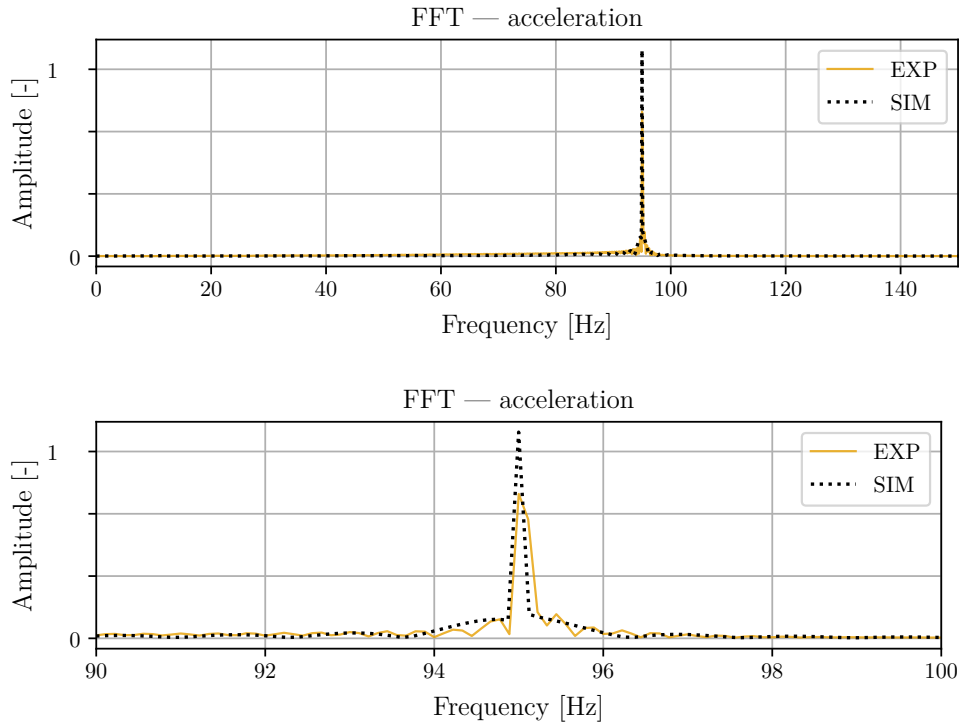


Figure 4.10: Frequency-domain comparison of the acceleration signal from the free-hanging plate test mounted in the frame. The plots show the full frequency range and a zoomed view around the operating frequency of the plate compactor. (Normalized)

The result from the center of mass calibration is presented in Table 4.4. Since the isolated MBD simulation is deterministic and was run with the same input conditions for each case, the simulated velocity is the same for every run. The average velocity of

the simulation was 0.9845 % of the average experiment velocity. This gives a relative error of ≈ 1.55 %, showing that the MBD model captures the overall forward motion of the compactor well.

Table 4.4: Average forward velocity in [m/s] for the calibration experiment and simulation. (Normalized against average experiment velocity)

Run	EXP	SIM
1	1.0001	0.9845
2	0.9845	0.9845
3	0.9882	0.9845
4	1.0242	0.9845
5	1.0030	0.9845
Average velocity EXP [m/s]		1.0
Average velocity SIM [m/s]		0.9845
Relative error [%]		1.55

5

Results

This chapter presents the validation of the coupled model using experimental data. The simulated results are compared with the measured response from the validation experiment. The collection of the experimental data, the simulation setup, and the post-processing procedure are described in Chapter 4. This chapter presents the results for one pass. Additional results are provided in Appendix B.

5.1 Acceleration response signal

The coupled model was evaluated by comparing acceleration, forward speed, pressure and point-cloud data. Comparing the data in the coupled model to the validation experiment will therefore view the accuracy of the base plate interaction to the substrate.

The acceleration comparison is shown in Figure 5.1. The result shows that the coupled model captures parts of the acceleration response, but the highest acceleration peaks are generally lower than in the test data. The vibration frequency is also captured, which is further supported by the frequency-domain comparisons shown in Figures 5.2 and 5.3. The operating frequency dominates at approximately $f = 95$ Hz. Smaller peaks are also observed around $f/2$ and $3f/2$.

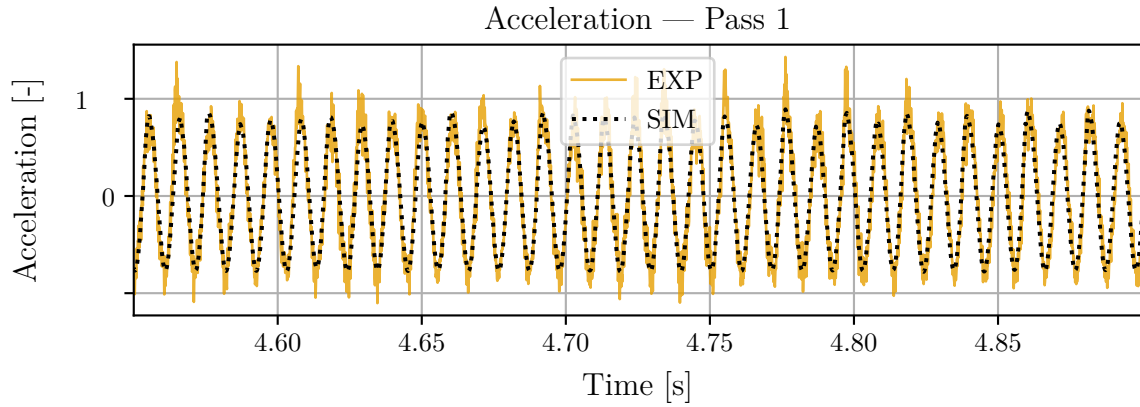


Figure 5.1: Normalized acceleration comparison between the validation experiment and coupled simulation. The signal is zoomed in and phase-shifted for visual comparison.

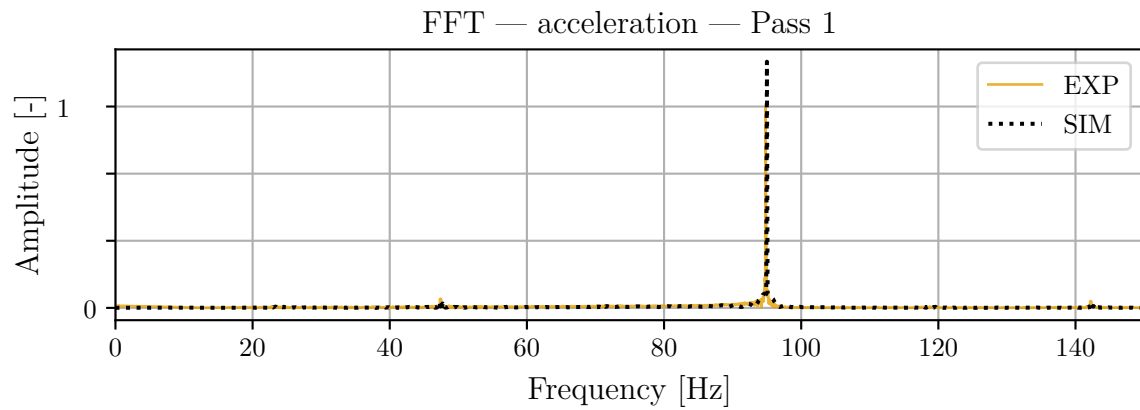


Figure 5.2: FFT comparison of the acceleration signal from the validation experiment and coupled simulation. (Normalized)

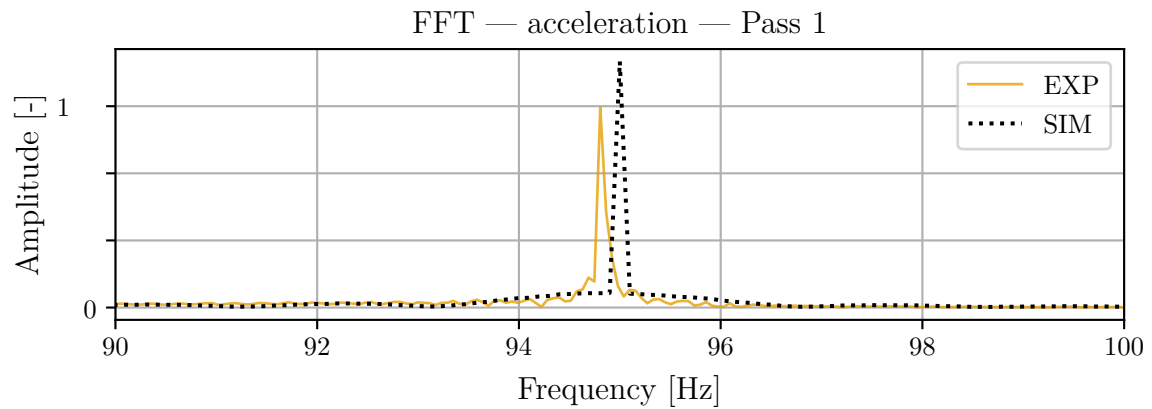


Figure 5.3: Zoomed FFT comparison of the acceleration signal from the validation experiment and coupled simulation around the operating frequency. (Normalized)

5.2 Forward speed

The forward speed of the plate in the isolated MBD model matched the test result with a relative error of 1.55 %. The forward speed comparison for the coupled model is presented in Table 5.1. The coupled simulation predicted a lower forward velocity than the validation experiment, with a relative error of 13.80 %. This indicates that the interaction between the plate and the substrate is not fully captured.

Table 5.1: Average forward velocity for the validation experiment and simulation. (Normalized against average experiment velocity)

Pass	EXP	SIM
1	0.9301	0.8033
2	0.9877	0.8398
3	0.9985	0.8559
4	1.0001	0.8641
5	0.9985	0.8731
6	1.0072	0.8731
7	1.0226	0.8690
8	1.0092	0.8772
9	1.0182	0.8842
10	1.0272	0.8796
Average velocity EXP		1.0
Average velocity SIM		0.8618
Relative error [%]		13.82

5.3 Pressure response signal

The raw pressure comparison for pass 3 is presented in Figure 5.4. The figure shows the pressure response both with the original output frequencies and with matched output frequency. With matched output frequency, the difference between the test and simulation pressure peaks is reduced.

Small negative values are observed in the experimental pressure signal. The cause of these values is not known, but they may be related to the measurement setup or signal processing. Similar negative values are not observed in the simulation, where pressure is calculated directly from the vertical force acting on the sensor area.

The peak pressure magnitudes for each sensor over pass 1–10 are shown in Figure 5.5. Both the test and simulation show an increasing pressure trend over the repeated passes, indicating that the bed response changes as the substrate becomes more compacted. This suggests that the substrate becomes stiffer and dampens less of the plate load as the particles settle and lock into each other.

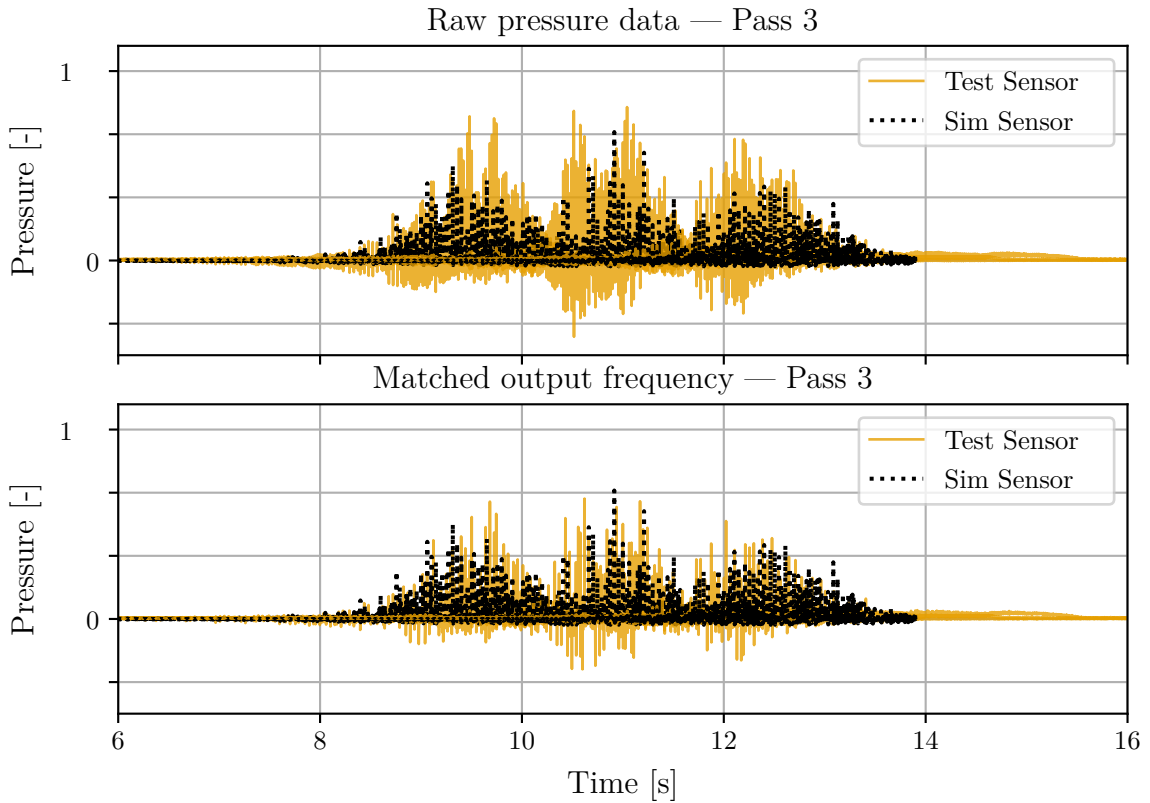


Figure 5.4: Normalized raw pressure data comparison from pass 3, shown with the original output frequencies and with matched output frequency.

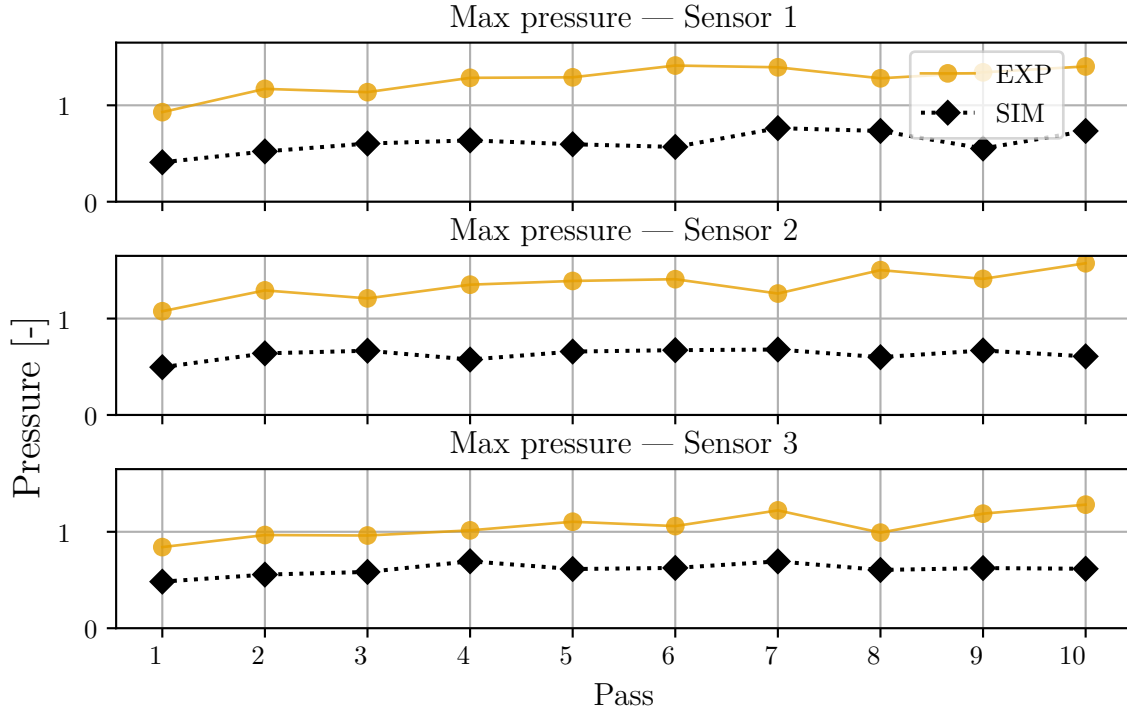
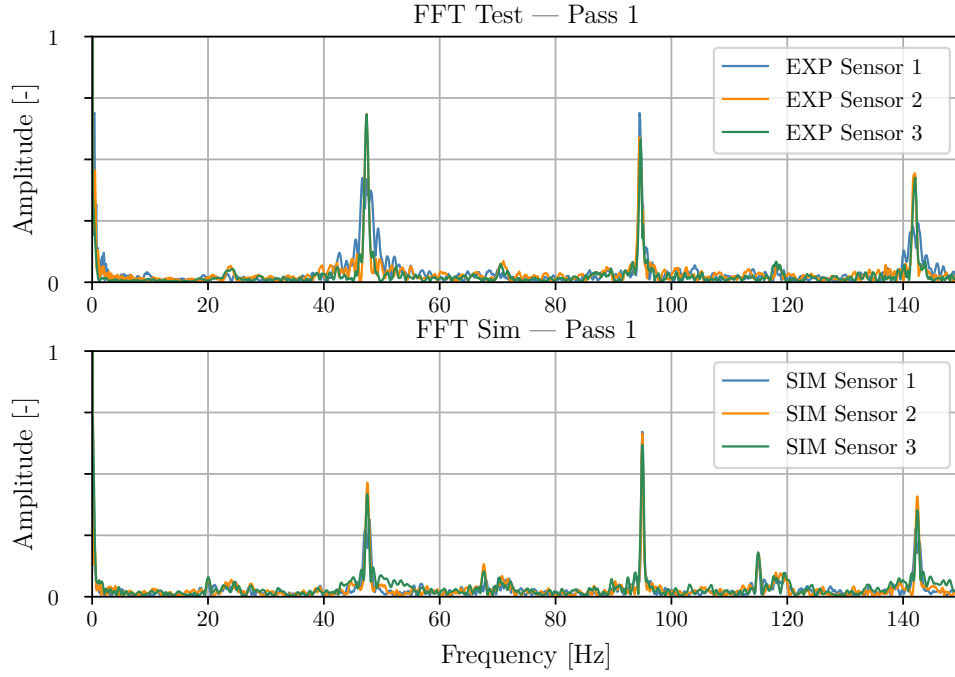
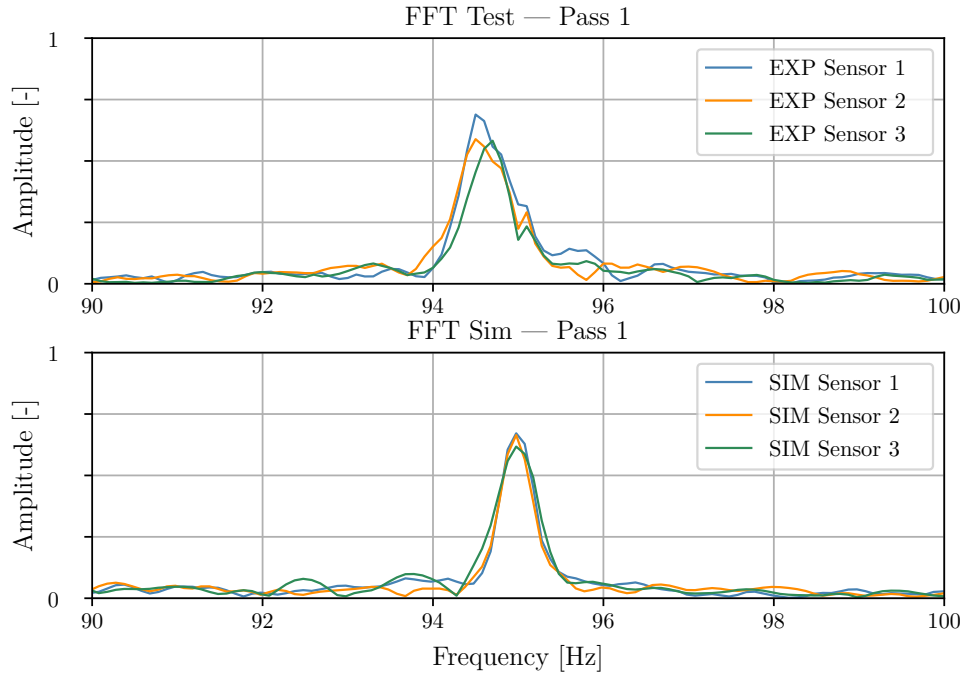


Figure 5.5: Peak pressure magnitude for each sensor over pass 1–10, comparing the validation experiment and coupled simulation. (Normalized)

A frequency analysis was also conducted for the pressure sensor data. The FFT results for pass 1 are shown in Figures 5.6a and 5.6b. The operating frequency at approximately $f = 95$ Hz is visible in both the test and simulation data. In addition, clear peaks are observed around $f/2$ and $3f/2$. Similar frequency components were also observed in the acceleration FFT for the coupled model, see Figure 5.2.



(a) Frequency comparison of the pressure sensor signals for pass 1. (Normalized)



(b) Zoomed frequency comparison of the pressure sensor signals for pass 1 around the operating frequency. (Normalized)

Figure 5.6: Frequency-domain pressure sensor results for pass 1.

5.4 Compaction Results

The average vertical displacement of the bed is compared in Figure 5.7. The test and simulation show a similar trend, although the magnitudes differ. In both cases, the displacement curve decreases with the number of passes. To study this trend more closely, the initial measurement, before any compaction was performed, is removed, and the first pass is used as the reference. This is shown in Figure 5.8.

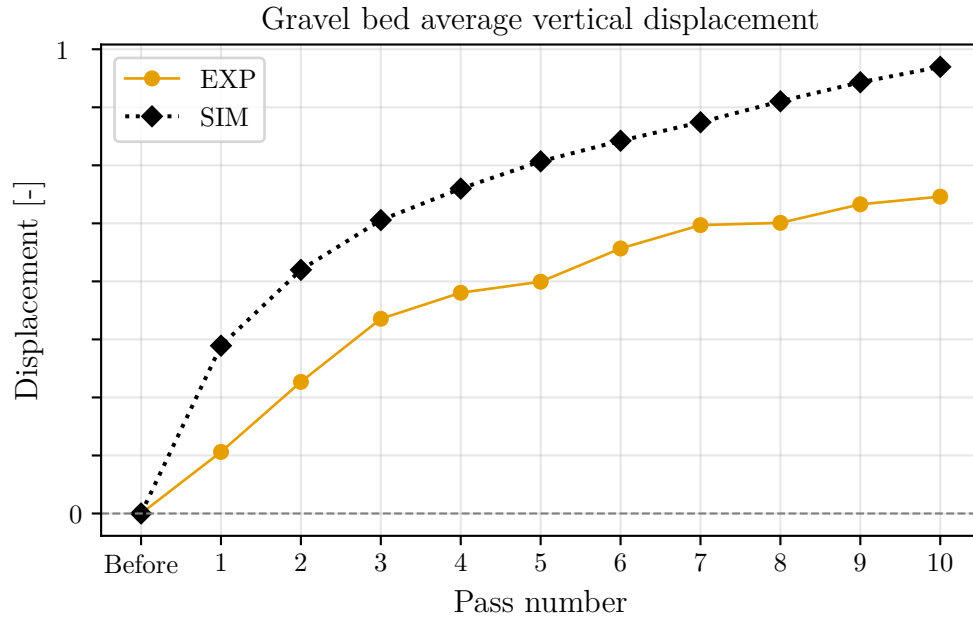


Figure 5.7: Average vertical displacement of the gravel bed validation. (Normalized)

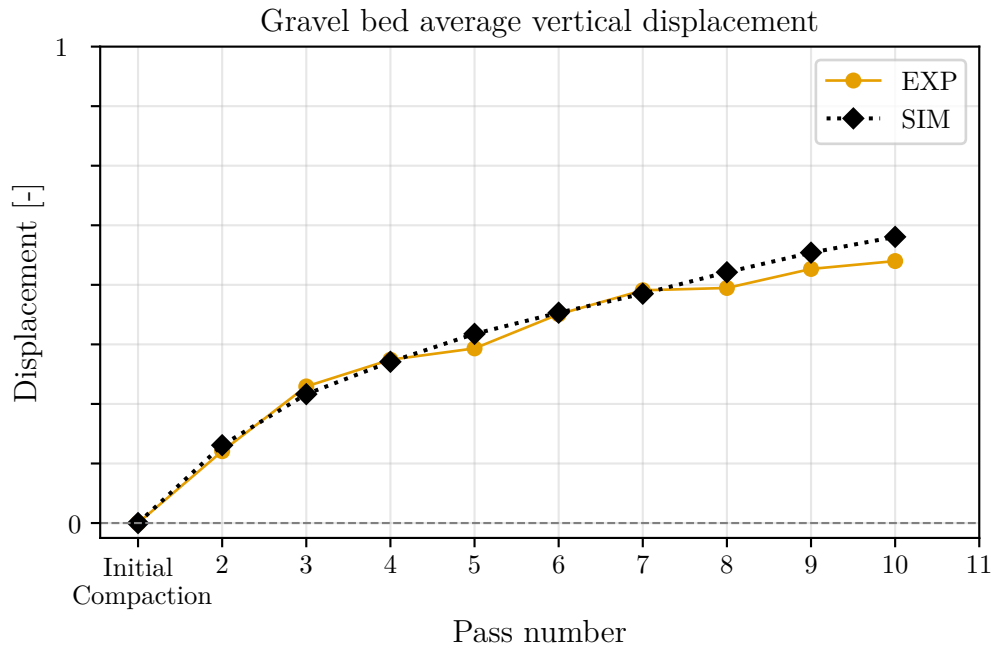


Figure 5.8: Average vertical displacement of the gravel bed validation, using the first pass as an initial compaction. (Normalized)

6

Discussion

The validation shows results indicating that the simulation overall captures the responses in the MBD and DEM model. There are differences in the magnitudes of the data, but the overall trend is captured. Studying the FFT from the pressure sensors in Figure 5.6a, the operational frequency of the compactor at $f = 95$ Hz is clear, together with peaks at $f/2$ and $3f/2$. This may indicate a double-bounce response, where the bottom plate interacts with the substrate more than once during some vibration cycles, while having little or no contact during other cycles. Since the bed surface is not even, the plate compactor may pitch and roll, which can be one cause of the uneven frequency response. This cannot be explained only as a local pressure sensor effect, since the same peaks are also seen in the acceleration FFT in Figure 5.2. This indicates that the response is connected through the substrate and the plate–substrate contact. The same peaks are not observed in the isolated MBD validation, see Figure 4.10, where the plate operates against a uniform soft mat instead of a granular substrate. This indicates that the additional frequency content is connected to the dynamic plate–substrate interaction. The fact that these frequency components appear in both the test and simulation data suggests that the coupled model captures important characteristics of this interaction.

The pressure readings in the sensors, both in the test and in the simulation, are somewhat stochastic. Gravel is not a homogeneous medium, and the force travels along paths formed by contact points between the particles. The gravel bed is in constant realignment, and new contact points are continuously formed. This causes the force paths to switch constantly and form paths resembling lightning bolts. An illustration of the force paths is shown in Figure 6.1. These paths can split during operation, meaning that the force is not guaranteed to reach the pressure sensor in a predictable way. Instead, a large portion of the force may be transferred elsewhere. This can cause uneven peaks that are not repeatable, which needs to be taken into consideration when studying magnitude validation of the pressure.

An additional source of uncertainty in the magnitude comparison is the difference in output frequency between the experimental data and the simulation data. While the experimental pressure sensors output data at 2000 Hz, the output frequency in the simulation was 400 Hz. At an operating frequency of 95 Hz, this means that there are roughly four data points per vibration cycle in the simulation, which will

be insufficient to accurately capture the pressure peaks.

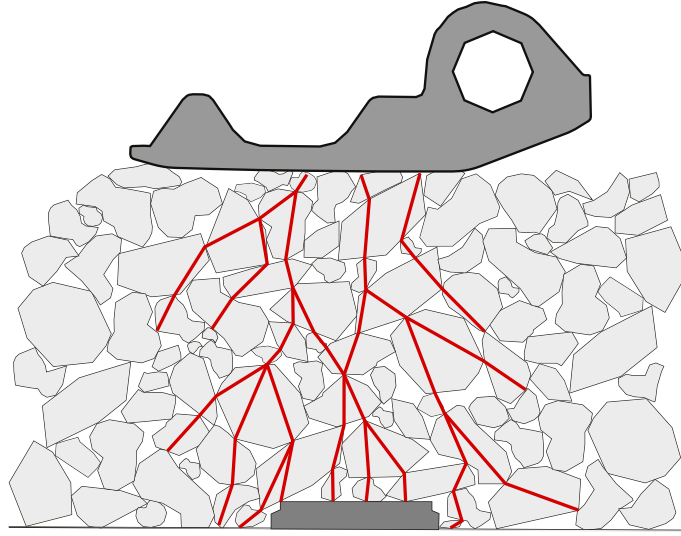


Figure 6.1: Illustration of force paths in substrate.

The average vertical surface compaction results shown in Figure 5.7 show that the simulation compacts the substrate more than the experimental data. The DEM model of the gravel only simulates convex particles, which results in only one contact point per particle-particle pair. Therefore, these particles do not fully capture the interlocking behaviour of real gravel. Interlocking increases the bed stiffness, since several contact points contribute to friction and mechanical locking between particles. As a result, the simulated bed does not fully capture the physical response of the real substrate.

This can partly be adjusted by increasing the particle-particle friction, so that each contact point contributes more resistance. However, this still does not fully represent the interlocking behaviour. Another effect of the contact friction is that the forward speed of the plate compactor is related to the friction between the plate and the substrate surface. With lower overall surface friction, the forward speed of the plate decreases, as seen in Table 5.1. Since the operating frequency remains approximately 95 Hz, a lower forward speed results in more compaction cycles per meter and thus larger vertical surface compaction.

However, when considering the results in Figure 5.8, where the first compaction pass is used as the reference, the curves show good agreement between the experiment and simulation. By using the first pass instead of the resting bed as the reference, the comparison becomes less dependent on the approximations made in the initial bulk volume study in Section 4.3.2. The estimated initial bed density may contain uncertainty due to assumptions in the measured volume, material distribution, and packing state. Therefore, the state after one compaction pass may provide a more comparable reference condition between the experiment and simulation. In this comparison, the first compaction pass acts as a normalization point, allowing the experimental and simulated gravel beds to have different initial states while still comparing the subsequent compaction trend.

7

Conclusion

This project has studied how an MBD and DEM model can be coupled for co-simulation. The simulation has been tested by visualization, and quantifiable measurement outputs can be read. These outputs have been validated against experimental data to see what conclusions can be made regarding the measurements. To conclude this thesis, this chapter will list the general conclusions regarding the complete model and experimental results that can be drawn from the project, and the more specific conclusions regarding the two models and their coupling

General conclusions

- An MBD model of a plate compactor and a DEM model of a granular substrate consisting of +16/-32 makadam can be coupled to interact with each other.
- The coupled model can produce quantifiable measurements for validation of acceleration on the compactor, pressure response at 30 cm depth in a particle bed, forward speed of the compactor, and particle bed vertical displacement caused by compaction.
- The model can be used to visualize the dynamics of the plate compactor and the responses of the substrate.
- Experimental data for +0/-32 and +16/-32 makadam show that the particle bed vertical displacement increases up until 8 passes for these materials.

Specific conclusions

- To keep the plate compactor model on its intended path, a torsion spring and a lateral bushing can be used to counteract yawing and drifting.
- The isolated plate compactor model manages to capture acceleration magnitude and frequency with no ground interference, but is unable to capture acceleration peaks in the coupled simulation with ground contact. However, it captures the operational frequency of the plate compactor well in both cases.
- Different output frequencies from simulation data and experimental data make validation somewhat unclear, since data peaks can be missed between the output frequency steps.
- Additional frequencies can be clearly seen in the pressure sensors, and to a smaller extent in the acceleration sensors, at $f/2$ and $3f/2$. These additional frequency responses are captured by the coupled simulation.
- The forward speed of the plate compactor is related to the ground stiffness and contact friction. However, this is difficult to adjust in a granular DEM model.

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A

Testing approach

This appendix shows the page from the testing approach document related to the validation experiment.

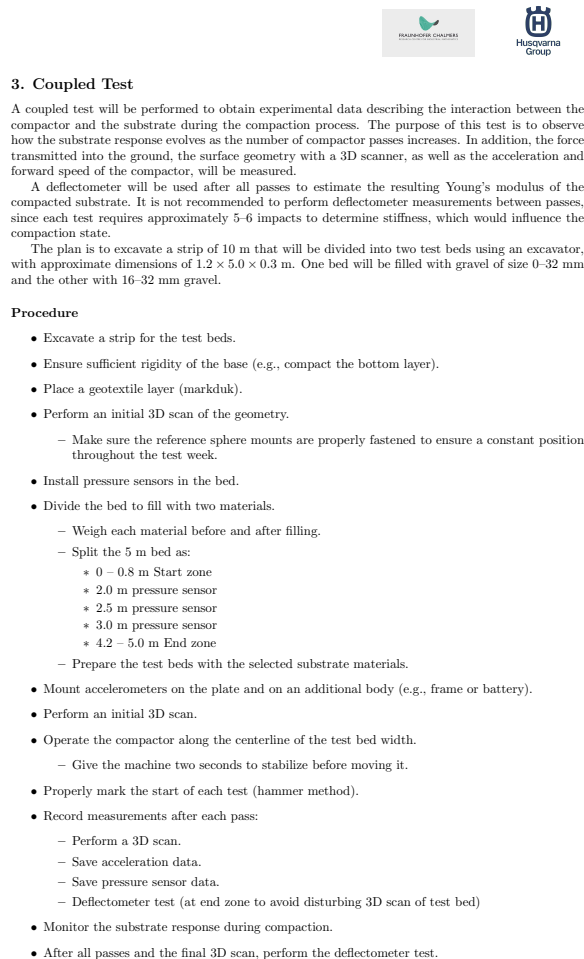


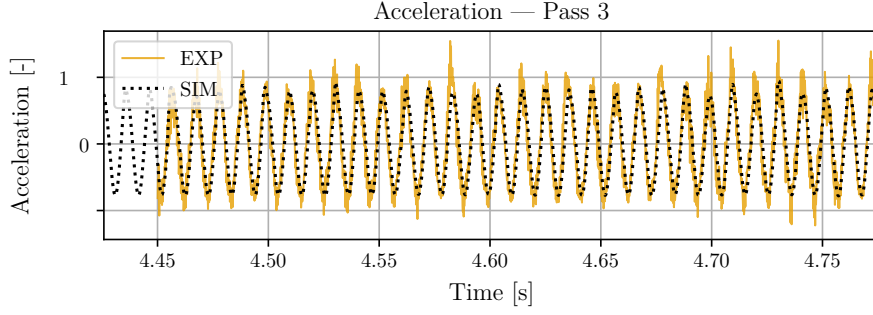
Figure A.1: Testing approach document page describing the coupled validation experiment.

B

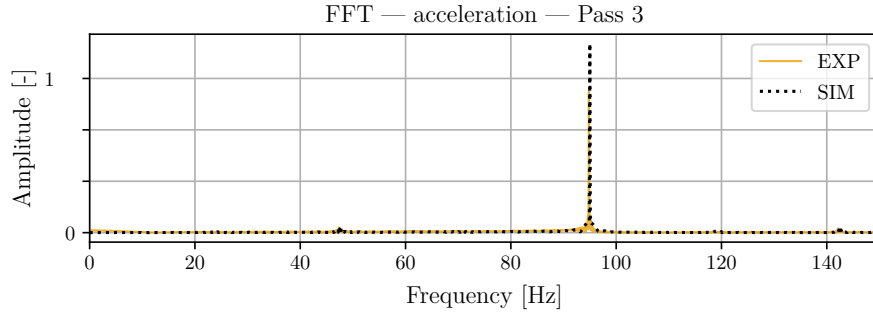
Additional Validation Results

B.1 Acceleration Response Signal

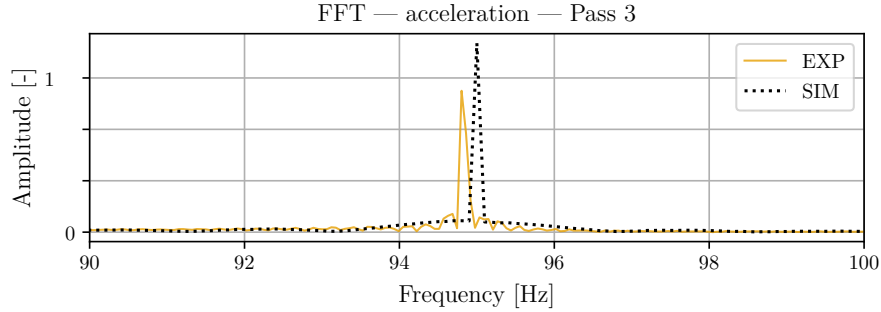
This section presents additional results from the acceleration validation of the coupled model. For some passes, the phase-shifted acceleration comparison did not show the complete signal due to the selected time window matching with the peak offset.



(a) Acceleration comparison between validation experiment and coupled simulation for pass 3. The signal is zoomed in and phase-shifted for visual comparison.

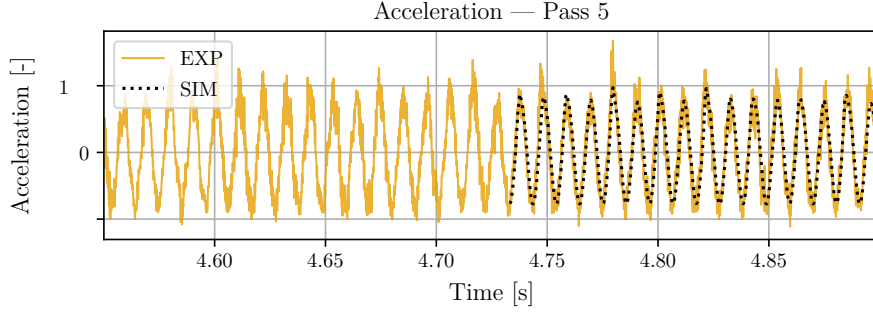


(b) FFT comparison of the acceleration signal from the validation experiment and coupled simulation for pass 3. (Normalized)

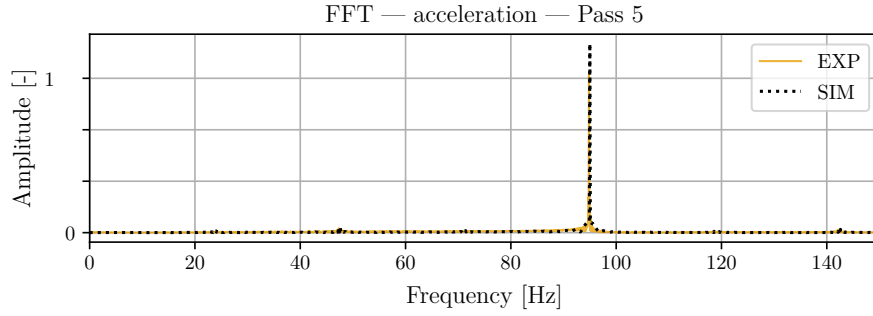


(c) Zoomed FFT comparison of the acceleration signal from the validation experiment and coupled simulation around the operating frequency. (Normalized)

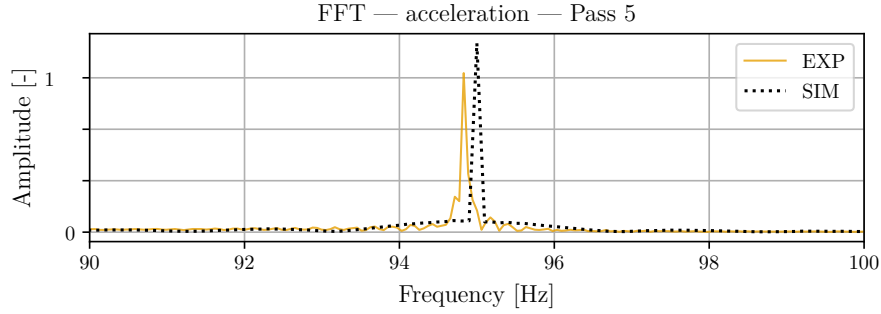
Figure B.1: Additional acceleration validation results for pass 3.



(a) Acceleration comparison between validation experiment and coupled simulation for pass 5. The signal is zoomed in and phase-shifted for visual comparison.

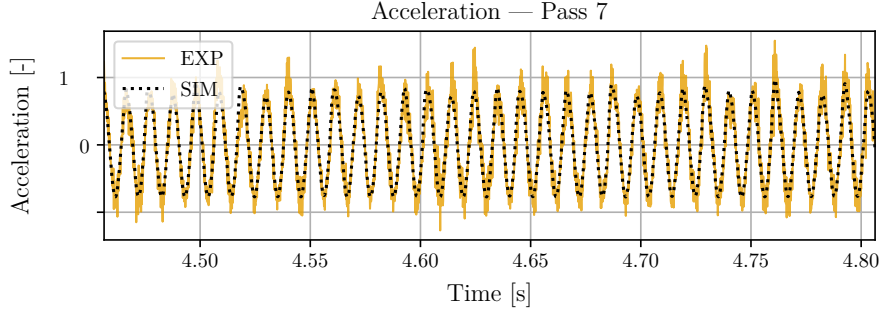


(b) FFT comparison of the acceleration signal from the validation experiment and coupled simulation for pass 5. (Normalized)

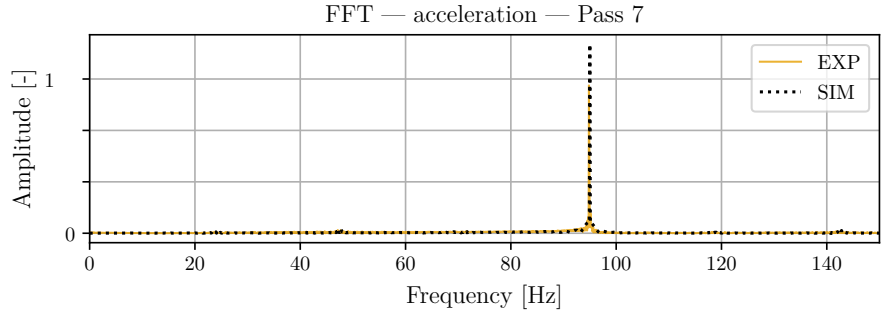


(c) Zoomed FFT comparison of the acceleration signal from the validation experiment and coupled simulation around the operating frequency. (Normalized)

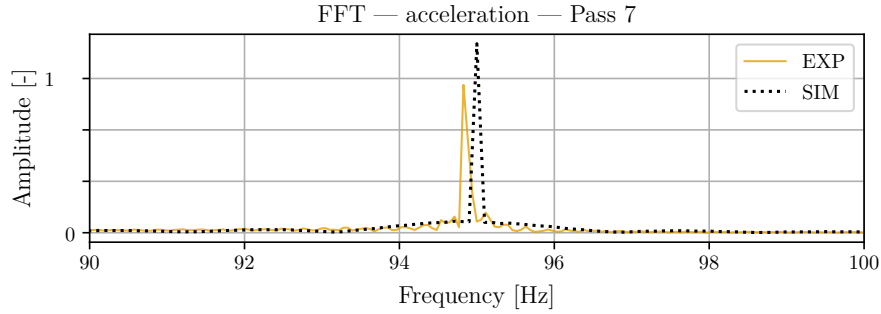
Figure B.2: Additional acceleration validation results for pass 5.



(a) Acceleration comparison between validation experiment and coupled simulation for pass 7. The signal is zoomed in and phase-shifted for visual comparison.

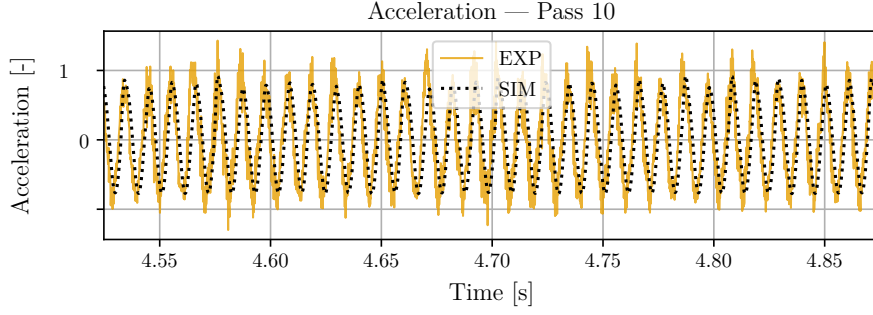


(b) FFT comparison of the acceleration signal from the validation experiment and coupled simulation for pass 7. (Normalized)

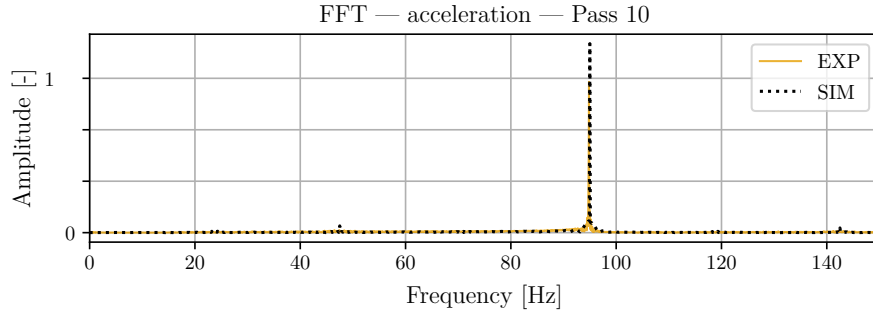


(c) Zoomed FFT comparison of the acceleration signal from the validation experiment and coupled simulation around the operating frequency. (Normalized)

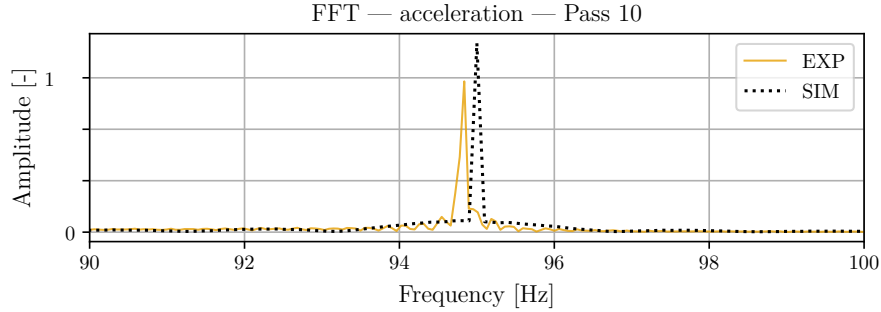
Figure B.3: Additional acceleration validation results for pass 7.



(a) Acceleration comparison between validation experiment and coupled simulation for pass 10. The signal is zoomed in and phase-shifted for visual comparison.



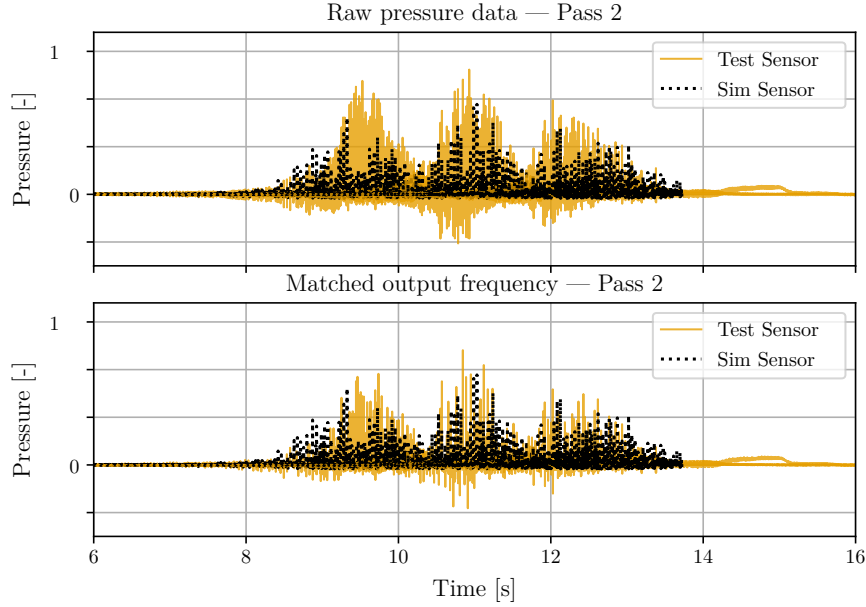
(b) FFT comparison of the acceleration signal from the validation experiment and coupled simulation for pass 10. (Normalized)



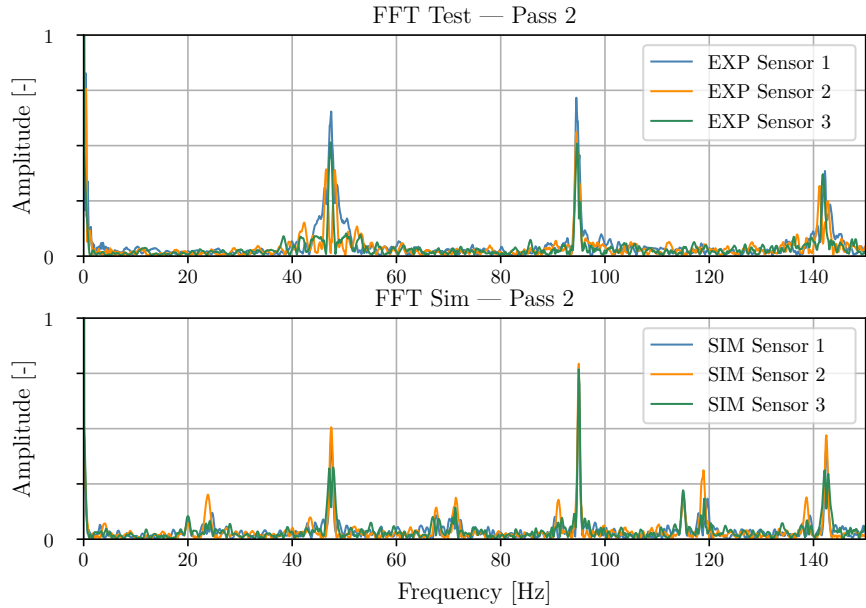
(c) Zoomed FFT comparison of the acceleration signal from the validation experiment and coupled simulation around the operating frequency. (Normalized)

Figure B.4: Additional acceleration validation results for pass 10.

B.2 Pressure Response Signal

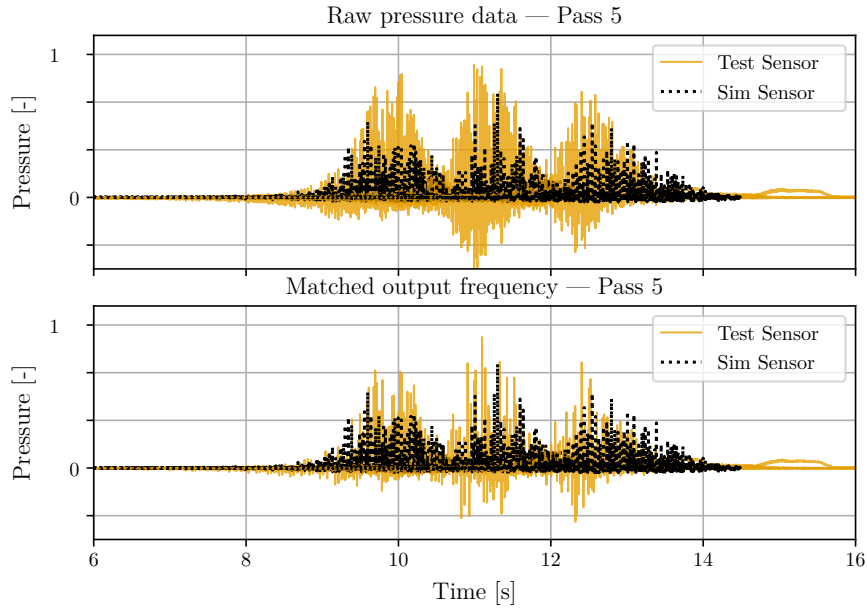


(a) Normalized raw pressure data comparison from pass 2, shown with the original output frequencies and with matched output frequency.

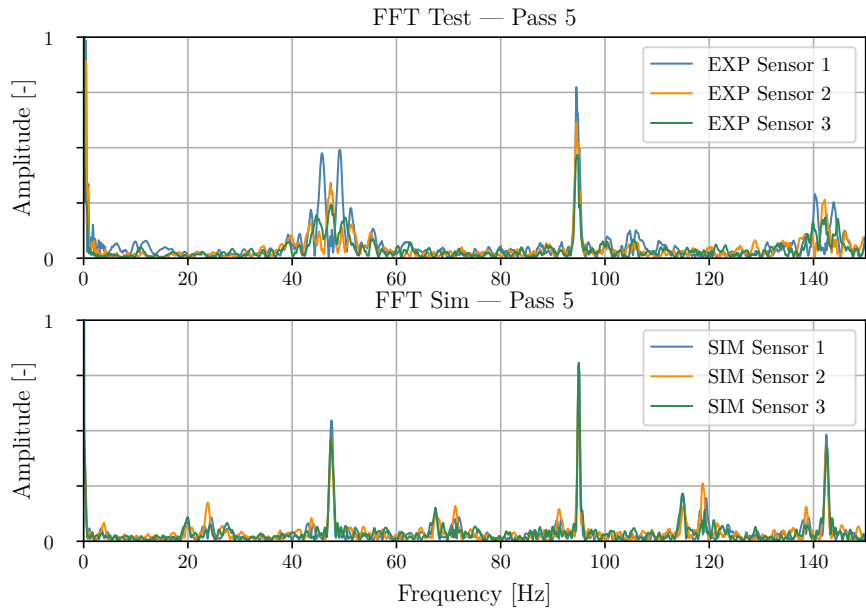


(b) Frequency comparison of the pressure sensor signals for pass 2. (Normalized)

Figure B.5: Additional pressure validation results for pass 2.

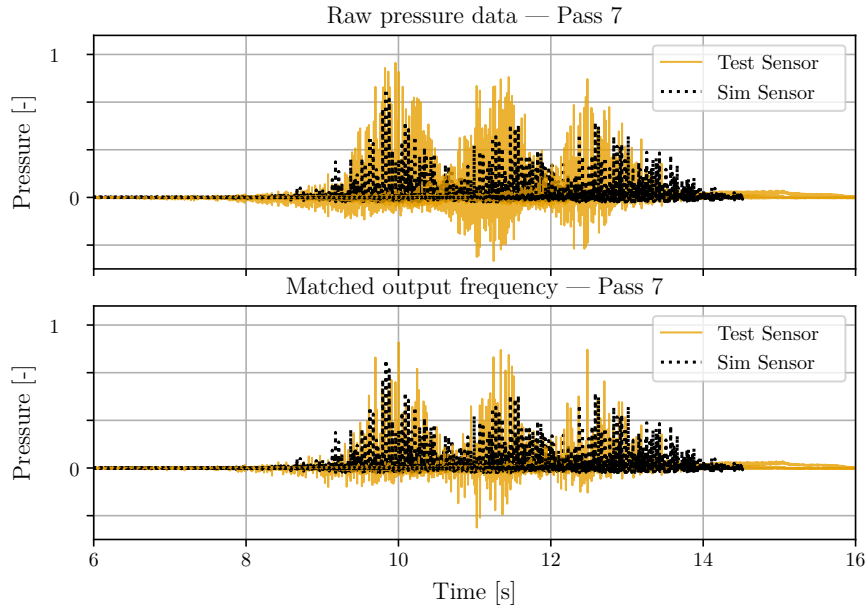


(a) Normalized raw pressure data comparison from pass 5, shown with the original output frequencies and with matched output frequency.

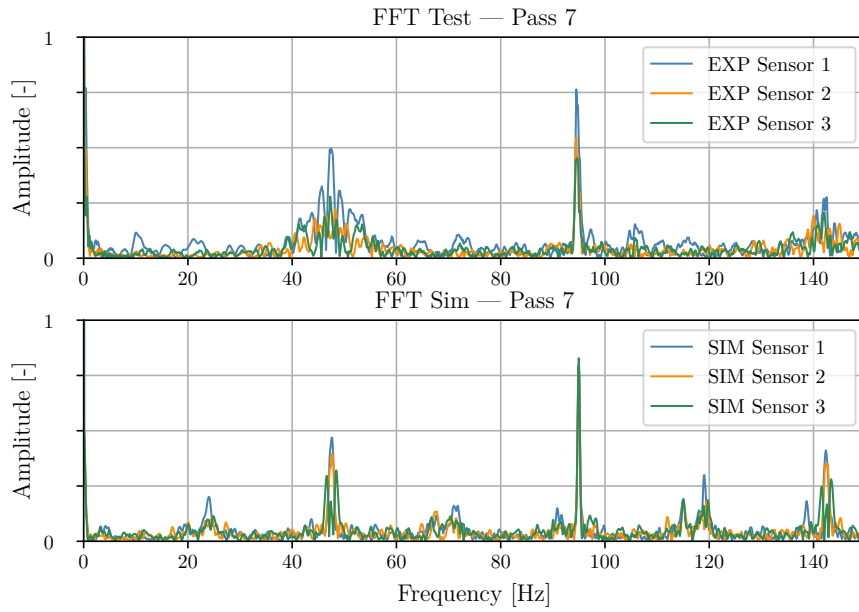


(b) Frequency comparison of the pressure sensor signals for pass 5. (Normalized)

Figure B.6: Additional pressure validation results for pass 5.

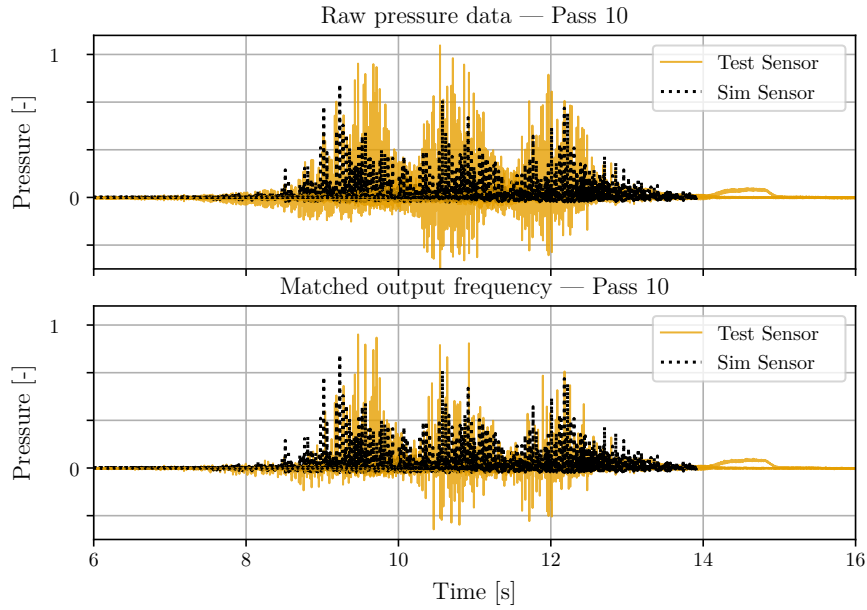


(a) Normalized raw pressure data comparison from pass 7, shown with the original output frequencies and with matched output frequency.

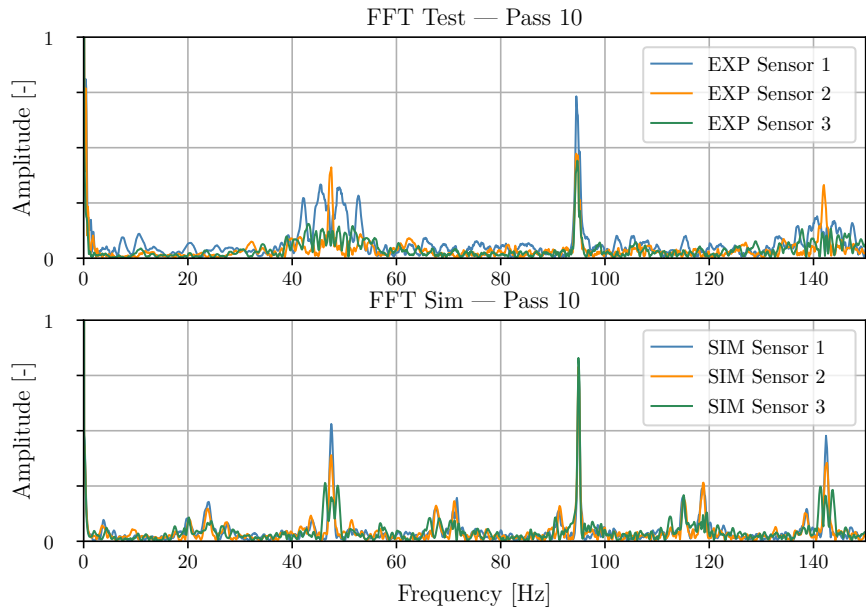


(b) Frequency comparison of the pressure sensor signals for pass 7. (Normalized)

Figure B.7: Additional pressure validation results for pass 7.



(a) Normalized raw pressure data comparison from pass 10, shown with the original output frequencies and with matched output frequency.



(b) Frequency comparison of the pressure sensor signals for pass 10 (Normalized)

Figure B.8: Additional pressure validation results for pass 10.

C

Experimental Comparison Between M1 and M2

This appendix presents additional experimental results comparing the two substrate materials. M1 refers to the 0–32 mm material, while M2 refers to the 16–32 mm material. The comparison is based on the measured compaction level and dynamic modulus.

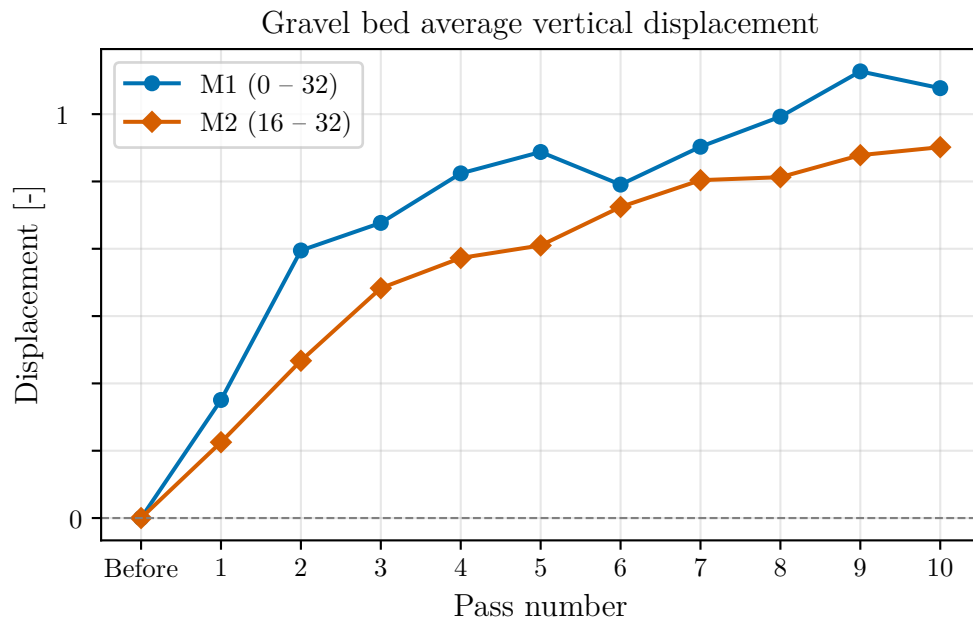


Figure C.1: Comparison of the measured normalized compaction level for substrate materials M1 and M2.

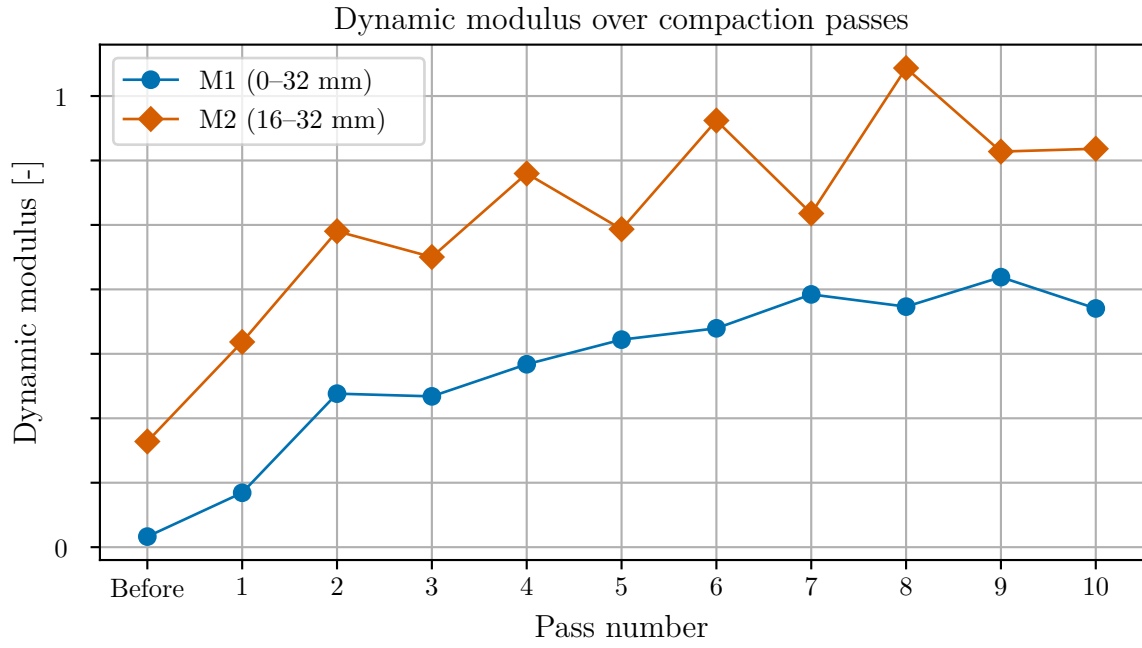


Figure C.2: Comparison of the measured dynamic modulus for substrate materials M1 and M2.

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