Impact of Geomaterial Properties and Roller Parameters on Intelligent Compaction Measurement Values Using Lumped Parameter Modeling

Jesús Castro Pérez
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IMPACT OF GEOMATERIAL PROPERTIES AND ROLLER PARAMETERS ON INTELLIGENT COMPACTION MEASUREMENT VALUES USING LUMPED PARAMETER MODELING

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INTELLIGENT COMPACTION MEASUREMENT VALUES USING
LUMPED PARAMETER MODELING

by

JESUS CASTRO PEREZ, BSCE

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
in Partial fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Civil Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

August 2021
Acknowledgments

First, I want to thank my parents for their unconditional love, patience, and support during my studies. My parents are the greatest blessing I have ever received. I am also grateful to my sister, brother-in-law, and three beloved nieces for being my inspiration.

I want to express profound appreciation to my advisor Dr. Soheil Nazarian for the opportunity to join the University of Texas at El Paso and work on this project. His patience and advice were essential during my academic journey. Furthermore, I want to thank Dr. Cesar Tirado for the lessons and time he provided to discuss my research and related concerns. I also thank Dr. Arturo Bronson for accepting being part of my thesis committee. Additionally, I feel thankful to Dr. Ivonne Santiago for allowing me to be the teaching assistant of her laboratory sessions. The trust she always deposited in me had a massive meaning during all my studies.

Also, I am grateful to UTEP for allowing me to learn from incredible professors and meet amazing people who later became friends. Last year was not easy, but it was enjoyable because of the friends I made. Arahim Zuñiga, for all those cups of coffee, endless conversations, and empathy, this work is also thanks to you. I would like to extend my gratitude to my friends Mariana Benitez and Selene Fernandez for their encouragement to complete this thesis and unique coffee recommendations, and to Carolina Hernandez for her time, constant motivation, and true friendship.

Last but not least, I thank the City of El Paso for adopting me and bringing loving, memorable, and welcoming people into my life.
Abstract

Roads consist of layers of geomaterials and asphalt or concrete to provide an optimal service life according to their exposure to traffic and the environment. Each layer that forms a pavement structure requires achieving specific quality and mechanical properties that are often obtained only through a proper compaction process.

Traditionally, compacted layers are tested using spot methods, which rely on the assumption that the properties measured from a small sample of material represent an entire section. This limitation has led to quality management techniques that continuously monitor the acceleration records from a sensor installed on the roller's drum. These techniques are known as Continuous Compaction Control (CCC) or Intelligent Compaction (IC), and their results are in terms of Intelligent Compaction Measurement Values (ICMV).

This study aims at developing a model through Simscape (Matlab™) that simulates soil compaction with a vibratory roller to characterize the relationships between the response of the drum and the mechanical properties of the compacted geomaterial. Since different roller manufacturers of IC rollers use different proprietary ICMV formulas, the Compaction Meter Value (CMV) and Compaction Control Value (CCV) are used throughout this study. This document summarizes the evaluation of changes in ICMV results from fluctuations in roller-specific characteristics.

A sensitivity analysis was performed to evaluate the impact of individual soil properties and roller parameters on the simulated CMV and CCV results. The overall results indicated that CCV provides results less sensitive to changes in individual roller-specific parameters than CMV. Additionally, CCV results maintained proportional values to simulated soil mechanical properties in most simulated scenarios, while CMV did not.
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Chapter 1. Introduction

1.1 Problem Statement

Proper compaction is an essential process in road construction. The best way to ensure proper compaction is appropriate quality control and quality assurance processes. Even though the quality of these materials has been evaluated with spot tests for more than 70 years, methods for continuously assessing the quality of the compaction have been proposed by many entities. The most common methods for this purpose are based on recording the acceleration of the drum during compaction operations (Forssblad, 1980; Thurner and Sandström, 1980). The analysis of the acceleration records to assess the stiffness of the geomaterial is carried out to implement the Intelligent Compaction (IC) or Continuous Compaction Control (CCC) concepts. These concepts enable engineers to evaluate the compaction quality on most compacted surfaces (Forssblad, 1980; Sandström and Pettersson, 2003; Thurner and Sandström, 1980).

Current IC practices use a wide variety of measurement values (referred to as the Intelligent Compaction Measurement Values, ICMVs) to determine the quality of the compacted geomaterials in pavements. In addition, different roller manufacturers often use different ICMVs for their commercial vibratory roller compactors. Therefore, a direct comparison of these measurement values is not a trivial task.

This thesis describes the development of a lumped spring-damper model that simulates the behavior of a geomaterial surface, a vibratory roller device during IC operations, and two commercially available ICMVs.
1.2 Objective

The objective of this thesis is to develop a model that simulates IC operations and evaluates the impact of roller characteristics in estimating geomaterials properties, particularly stiffness and ICMVs.

1.3 Organization

Aside from this chapter, this document is structured into seven chapters. Chapter 2 contains a literature review of vibratory roller compaction, ICMV, and numerical modeling techniques used to model compacted geomaterials. Chapter 3 addresses the development of the model that simulates the roller vibratory compaction. This chapter also addresses the configuration of the model components, drum-soil interaction, and the methodology applied to calculate soil stiffness from roller motion records. Chapter 4 lists the roller-dependent values that influence the measured ICMVs. These values include static weight, operating frequency, eccentric force, and the suspension system of the drum-frame interface. This chapter also addresses the results of a sensitivity study that evaluates various scenarios of vibratory roller compactors and their responses. Finally, Chapter 5 summarizes activities, conclusions, and recommendations for future research.
Chapter 2. Literature Review

The quality of a pavement layer is directly associated with the compaction quality it has been subjected to. Since vibratory rollers are frequently used for compaction, it is necessary to understand how the roller characteristics influence the compaction results. This chapter summarizes relevant research performed on compaction through vibratory rollers. The literature review consists of (1) a description of compaction through vibratory rollers, (2) an examination of the interaction between the roller and soil during IC operations at a fixed vibration rate, (3) a summary of the theoretical background of current intelligent compaction measurement values (ICMVs) and (4) an explanation of the numerical techniques that have been used to estimate the mechanical properties from data collected from IC operations on geomaterials.

2.1 Vibratory Roller Compaction

The process of compacting geomaterials improves the mechanical properties of a given layer used for a pavement structure. Transforming loosely placed granular and mildly cohesive soils into densely packed load-bearing earth structures commonly involves vibratory roller compactors (van Susante and Mooney, 2008). For certain types of soils, the vibratory rollers compact more efficiently than non-vibratory rollers that use their static weights alone (Facas, 2010; Neff, 2013).

Vibrations during compaction generate dynamic forces resulting in increased vertical loadings that facilitate compaction. An example of a rotating mass mechanism generating dynamic loads is shown in Figure 1. The drum vibration is stemmed from an eccentric mass within the drum that is continuously shifted concentrically to the longitudinal axis of the drum (Pistrol et al., 2016). Thus, the magnitude of the dynamic force generated by the drum's vibration is proportional to the
eccentricity of the drum's internal mass and the operational vibratory frequency at which the roller operates.

Figure 1. Drum excitation mechanism inside a vibratory roller (Adam, 1996).

Considering that compaction depths are proportional to the magnitude of the resultant compacting load, operational frequency and amplitude of eccentricity may be customized to achieve the specific goals of a given compaction assignment. The other main components of a vibratory roller considered in this work are the mass of the frame and the damping and stiffness coefficients of the drum-frame interface.

2.2 Review of Drum-Soil Interaction

Adam (1996), Adam and Kopf (2004), and Pistrol et al. (2016) defined the different modes in which the drum interacts with the soil during compaction practices. As shown in Figure 2, most of these interaction modes are classified based on the existence or pattern of the drum's decoupling from soil (also referred to as "loss of contact"). In general, the modes may be classified as periodic or chaotic. The continuous contact mode is characteristic of soils with low stiffness or compaction practices with vibratory rollers operating at low amplitude and low vibration frequency. Vibratory rollers operate in permanent contact with the soil when the maximum contact force is less than two times the machine's static weight (Anderegg and Kaufmann, 2004). Otherwise, the mode changes to the "periodic loss of contact" mode.
The partial uplift interaction mode occurs when the vertical force created by a combination of eccentric amplitude and drum masses causes a periodic loss of contact at a constant frequency. Partial uplift is also the target interaction between drum and soil by manufacturers because it is the most efficient mode of operation and optimizes compaction with vibratory rollers.

### Table: Observed modes of vibratory rollers interaction with soil

<table>
<thead>
<tr>
<th>Drum Motion</th>
<th>Interaction (drum-soil)</th>
<th>Operating Condition</th>
<th>Soil Contact Force</th>
<th>Application of CCC</th>
<th>Soil Stiffness</th>
<th>Roller Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periodic</td>
<td>Continuous contact</td>
<td>CONT. CONTACT</td>
<td>yes</td>
<td>low</td>
<td>fast</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Partial Uplift</td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double Jump</td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chaotic</td>
<td>Chaotic Motion</td>
<td>no</td>
<td>no</td>
<td>high</td>
<td>slow</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Observed modes of vibratory rollers interaction with soil (Adam, 1996; Adam and Kopf, 2004)

Double jump is a mode of interaction typical of increased soil stiffness when the drum produces a high jump in every two oscillations and a relatively smaller one in the oscillation in-between. The energy of the impact when the roller’s drum touches the soil surface after "jumping" is proportional to the jump's amplitude (or height). Therefore, the highest energy and compaction are transmitted to the soil in every other oscillation. Although this may provide the required compaction, it considerably decreases the lifespan of the roller.

A rocking motion occurs when there is a differential settlement due to the compaction along a roller movement direction. This settlement causes the vibratory roller to be tilted to one
side. Rocking motion makes more difficult the operation of the vibratory roller than the previously mentioned ones.

High heterogeneity in soil mechanical properties and non-ideal roller operating parameters cause a non-periodic loss of contact, known as chaotic motion. Like the rocking motion, this mode of operation is not recommended for compaction practices because their associated dynamic behavior may be unstable and erratic (Anderegg and Kaufmann, 2004).

Among the "continuous contact," "partial uplift," "double jump," "rocking motion," and "chaotic motion" modes, only the continuous contact, partial uplift, and double jump are recommended for intelligent compaction (IC) practices from all these modes of drum-soil interaction.

2.3 Intelligent Compaction Measurement Values

Currently, spot tests with devices such as the nuclear density gauge (NDG), plate load test (PLT), and the lightweight deflectometer (LWD) are the primary tools for quality management of compacted geomaterials in the United States and Europe (Nazarian et al., 2020). However, the spots tested with these devices do not necessarily represent the overall quality nor homogeneity of the compaction work (Thurner and Sandstrom, 2000). In other words, a shortcoming of spot testing is that weak areas of a compacted section can be missed.

There is an implicit need for test methods capable of assessing the quality of an entire compacted section. A correlation between soil stiffness and the motion behavior, as noticed during an experimental field test with a vibratory roller in 1974 (Pistrol et al., 2016), resulted in the basic concept of intelligent compaction (IC) through continuous compaction control (CCC) systems. A CCC system, in general, consists of using the vertical component of the drum acceleration in time
and frequency domain to determine the quality of the compacted pavement material (Mooney and Adam, 2007).

During the following decades, the continuous development of this technology resulted in different methodologies to estimate the quality and homogeneity of compaction using information obtained from sensors installed on vibratory rollers. The results of these methodologies are in terms of Intelligent Compaction Measurement Values (ICMV). Commercially available ICMV with the vibratory drum parameters needed for their calculation are briefly described in Table 1 (Mooney et al., 2010). This thesis will only address the Compaction Meter Value (CMV) and Compaction Control Value (CCV). Both ICMVs are unitless parameters used to estimate mechanical properties using data obtained during IC operations.

2.3.1 Compaction Meter Value (CMV)

The Compaction Meter Value (CMV) was introduced by the roller manufacturer Dynapac, in cooperation with Geodynamic, in the late 1970s (Mooney and Adam, 2007). CMV is calculated from acceleration records in the frequency domain, as illustrated in Figure 3. Also, CMV is defined as the ratio of the amplitudes of the accelerations at the fundamental frequency \( A_\Omega \) and at the second fundamental frequency \( A_{2\Omega} \) multiplied by a constant \( c \):

\[
CMV = c \frac{A_{2\Omega}}{A_\Omega}
\]  

The value of constant \( c \) is often established as 300 or 100. The plots, results, and discussions addressed in this document will use a \( c \) value of 100 for CMV calculations.

2.3.2 Compaction Control Value (CCV)

The Compaction Control Value (CCV) is the ICMV commercially introduced by roller manufacturer Sakai. CCV also utilizes the acceleration records in the time domain collected from
a sensor attached to the vibratory drum. As shown in Figure 4, the calculation of CCV involves measuring up to six amplitudes of acceleration at different frequencies (Eq. 2). Acceleration peaks at subharmonic frequencies are the expected result of a "Double Jump" interaction mode. Therefore, CCV results are inferred to be more sensitive to all the roller-soil interaction modes.

\[
CCV = 100 \times \left[\frac{A_{0.5\Omega} + A_{1.5\Omega} + A_{2\Omega} + A_{2.5\Omega} + A_{3\Omega}}{A_{0.5\Omega} + A_{\Omega}}\right]
\]  

(2)

Table 1. Commercially available roller measurement values (Mooney et al., 2010)

<table>
<thead>
<tr>
<th>Measurement Value</th>
<th>Manufacturer</th>
<th>Parameter Used</th>
<th>Relations Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compaction Meter Value (CMV)</td>
<td>Dynapac, Caterpillar, Hamm, Volvo</td>
<td>The ratio of vertical drum acceleration amplitudes fundamental vibration frequency ( (A_0) ) and its first harmonic ( (A_{2\Omega}) ).</td>
<td>[ CMV = c \frac{A_{2\Omega}}{A_\Omega} ]</td>
</tr>
<tr>
<td>Compaction Control Value (CCV)</td>
<td>Sakai</td>
<td>Relationship of multiple acceleration amplitudes at harmonics and subharmonics of fundamental frequency ( (A_{0.5\Omega}, A_{\Omega}, A_{1.5\Omega}, A_{2\Omega}, A_{2.5\Omega}, \text{and} A_{3\Omega}) ).</td>
<td>[ CCV = 100 \times \left[\frac{A_{0.5\Omega} + A_{1.5\Omega} + A_{2\Omega} + A_{2.5\Omega} + A_{3\Omega}}{A_{0.5\Omega} + A_{\Omega}}\right] ]</td>
</tr>
<tr>
<td>Stiffness ( (K_s-A) )</td>
<td>Ammann</td>
<td>Vertical drum displacement ( (z_d) ), eccentric mass moment ( (m_0e_0) ), drum mass ( (m_d) ), and rotational frequency ( (\Omega) )</td>
<td>[ K_{s-A} = \Omega^2 \times \left[ m_d + \frac{m_0e_0}{z_d} \right] ]</td>
</tr>
<tr>
<td>Vibration Modulus ( (E_{vb}) )</td>
<td>Bomag</td>
<td>Maximum vertical drum displacement ( (z_d) ), contact force ( (F_c) ), Poisson ratio ( (\nu) ), Drum’s length and radius ( (L \text{ and } R, \text{ respectively}) ), and contact width ( (b) ).</td>
<td>[ z_d = \frac{2 \times (1 - \nu^2)}{\pi E_{vb}} \times \frac{F_c}{L} \times \left(1.8864 + \ln \frac{L}{b}\right) ] where: [ b = \sqrt{\frac{16R(1-\nu^2)F_c}{\pi EL}} ]</td>
</tr>
<tr>
<td>Machine Drive Power (MDP)</td>
<td>Caterpillar</td>
<td>Difference of gross power and the power associated with sloping grade and machine loss.</td>
<td>[ MDP = P_g - WV \left( \sin \theta + \frac{a}{g} \right) - (mV + b) ] where ( P_g ) is gross power, ( W ) is roller weight, ( a ) is acceleration, ( g ) is the acceleration due to gravity, ( \theta ) is slope angle, ( V ) is roller velocity, ( m ) and ( b ) are internal loss coefficients.</td>
</tr>
</tbody>
</table>
According to (Mooney et al., 2010), both CCV and CMV were determined insensitive to variations in soil properties when providing values below 10 (unitless result considering $c = 300$ for CMV calculations). Soft soils are not likely to generate acceleration amplitudes at harmonic and subharmonic frequencies. Variations in CCV and CMV results are nearly meaningless when there is a single peak in the amplitude acceleration record in the frequency domain.
2.4 Numerical Modeling Techniques of Compacted Geomaterials

The lumped parameter modeling techniques have been used to simulate the interaction of a vibratory roller with soil during IC operations (Anderegg and Kaufmann, 2004; van Susante and Mooney, 2008). These techniques model the vertical component of the drum motion during compaction and the interaction in which the roller transfers a dynamic load to the soil (Neff, 2013).

Lumped parameter models allow simulating the response of soil, considering static masses, the stiffness and damping coefficients of the drum-frame suspension system, soil stiffness and damping, and displacements of each of the components. As shown in Figure 5, van Susante and Mooney (2008) used a three-degree-of-freedom (3DOF) model, which considered the frame, drum, and soil as three different masses with their corresponding motions. The mass of the frame, drum, and soil are represented as $m_f$, $m_d$, and $m_s$, respectively. Soil stiffness and drum-frame suspension stiffness are represented with $K_s$ and $K_{D-F}$, respectively. On the other hand, soil and drum-frame suspension damping parameters $C_s$ and $C_{D-F}$ that restrain vibratory motions are essential to simulate the compaction of geomaterials through a spring-damper system.

2.5 Contact Force

Although the contact force cannot be measured directly, this force may be estimated from the lumped parameter models, knowing the mass of the roller's drum and frame and corresponding acceleration records. Estimation of contact force has been attempted with available IC information, neglecting the frame’s mass inertia due to lack of frame acceleration records (Anderegg and Kaufmann, 2004). Frame's acceleration records improve the estimation of the contact force by adding the influence of dynamic forces of the frame suspension into the calculations.

The development of a lumped parameter model to simulate IC operations includes developing an equation to calculate the contact force when the motion records of each model mass
element are available. This contact force development is addressed in detail in Chapter 3 of this document.

![Diagram of a 3DOF lumped parameter model](image)

Figure 5. 3DOF lumped parameter model (van Susante and Mooney, 2008).

### 2.6 Summary

A summary of the objectives, scopes, and key findings of relevant literature to IC and CCC practices is shown in Table 2. Both CMV and CCV can indicate changes in the stiffness of a geomaterial layer subjected to compaction. The calculation of CMV and CCV requires the acceleration amplitudes at the fundamental frequency and, at least, a harmonic frequency. The distribution of drum acceleration amplitude peaks in the frequency domain graphs may characterize the drum-soil interaction during IC operations. Lumped parameter models have been proved capable of simulating IC by matching model results with field data collected during IC and extracting mechanical properties of the geomaterials.
Table 2. Literature review of intelligent compaction and lumped parameter models.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Objective and Scope</th>
<th>Key Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thurner and Sandstrom (2000)</td>
<td>Described the background and principle of continuous compaction control, compaction standards, and applications.</td>
<td>Defined CMV as the ratio of the acceleration amplitude at the fundamental frequency, and at the first harmonic of the operating frequency. CCC can increase the efficiency and homogeneity of the compaction works.</td>
</tr>
<tr>
<td>Anderegg and Kaufmann (2004)</td>
<td>Evaluated application potential of feedback control systems in automatic compaction and compaction control based on the theory of nonlinear oscillations.</td>
<td>Vibratory rollers operate in permanent contact with the soil when the maximum contact force is less than two times the machine's static weight. Otherwise, the interaction changes to the &quot;periodic loss of contact&quot; mode.</td>
</tr>
<tr>
<td>(Mooney and Adam, 2007)</td>
<td>Provided an overview of ICMV history and theoretical background for measuring soil properties during IC operations.</td>
<td>ICMVs provide a relative measure of soil stiffness changes during compaction.</td>
</tr>
</tbody>
</table>
| van Susante and Mooney (2008)    | - The evaluated capability of 3- and 4-degree-of-freedom lumped parameter models with linear and nonlinear elements.  
- Reproduced vibratory roller behavior observed experimentally by considering the loss of contact. | Drum-frame-soil lumped parameter models with nonlinear soil stiffness can capture soil parameters from roller vibration data. |
| Facas et al. (2010)              | Verified a lumped parameter roller/soil model using field data collected over a range of excitation frequencies on spatially homogeneous soil and transversely heterogeneous soil | Rotational motion may occur in both homogeneous and heterogeneous soil. Directional independence in roller-measured soil stiffness can be achieved using vertical vibration data at the drum center of gravity. |
| Mooney and Facas (2013)          | - Developed a methodology to extract composite soil stiffness values from available vibratory IC rollers.  
- Explain the influence of individual pavement layer properties on the soil stiffness measured by IC rollers | Forward model results match with available experimental data. The calculated soil stiffness increases proportionally to increments in both maximum drum displacement and contact force. |
| Pistrol et al. (2016)            | - Discussed measurement principles and theoretical background of various ICMVs  
- Compared results of large-scale tests using each of the ICMVs. | "Double Jump" drum-soil interaction mode results in an additional peak at a subharmonic frequency on the acceleration record. |
| Nazarian et al. (2019)           | - Developed procedures to estimate the mechanical properties of geomaterials using IC technology.  
- Summarized current specifications for implementing IC technology. | Stiffness-based specifications are almost a real-time approach for determining field target values. Unlike spot testing methods, ICMV can provide quality control on entire compacted sections. |
Chapter 3. Development of Lumped Parameter Model

This chapter describes the discrete lumped parameter model representing the roller-soil interaction developed and utilized in this study to assess the pavement response due to roller compaction. The discrete lumped parameter model is based on the model proposed by van Susante and Mooney (2008). The model simulates the mechanical impact and motion generated by the operation of a vibratory roller during IC operations.

3.1 Model Concept

The developed lumped parameter model intends to simulate the behavior of a vibratory roller of interest against a specific geomaterial with specific mechanical properties. Although this model does not consider soil elastic modulus as input and only considers springs and viscous dampers, elastic modulus can be calculated as discussed at the end of this chapter.

The characteristics of the vibratory roller and properties of soil are modeled with a series of input parameters. These input parameters influence the total response of the soil (or geomaterial surface). As shown in Figure 6a, the development of a lumped parameter models the roller’s frame, vibratory drum, suspension system, and soil as a component able to generate inertial forces and influence the overall motion. The soil is modeled as a mass connected to a spring-damper suspension system that simulates the reaction of the soil against the vertical dynamic loading that the vibratory roller generates.

The mass of the soil is assumed as a fraction of the drum mass. The considered apparent soil mass has varied from zero (neglecting soil mass) to 62% of the drum mass in similar models (van Susante and Mooney, 2008), and recent publications used a value of 30% (Mooney and Facas, 2013). The model developed in this thesis is a lumped model that also considers decoupling (or loss of contact) of the vibratory drum from the geomaterial subject to IC operations, as shown in
Figure 6b. The frame and drum are connected through a spring-damper suspension system ($K_{D,F}$ and $C_{D,F}$, respectively). The static weight of the frame and drum plus the dynamic forces generated through vibration are transferred to the soil when the drum and the soil surface are in contact. The dynamic vertical excitation force ($F_{ecc}$) as a function of time ($t$) is calculated from

$$F_{ecc} = m_0 e_0 \Omega^2 \sin(\Omega t).$$

(3)

The parameters related to this equation are defined in Table 3. As shown in Figure 2, the consideration of the loss of contact is essential to simulate all the drum-soil interaction modes. Allowing the loss of contact in a lumped model is necessary for proper simulation of drum-soil interaction modes during IC operations.

Figure 6. (a) Vibratory roller lumped model with drum-soil contact. (b) Representation of lumped model during a loss of contact.
Table 3. Description of input parameters in lumped model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum mass</td>
<td>( m_d )</td>
<td>kg</td>
</tr>
<tr>
<td>Frame mass</td>
<td>( m_f )</td>
<td>kg</td>
</tr>
<tr>
<td>Soil mass</td>
<td>( m_s )</td>
<td>kg</td>
</tr>
<tr>
<td>Operating Amplitude</td>
<td>( A )</td>
<td>mm</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>Rotational Frequency</td>
<td>( f )</td>
</tr>
<tr>
<td>Eccentric mass moment</td>
<td>( m_0e_0 )</td>
<td>Kg·m</td>
</tr>
<tr>
<td>Drum-frame stiffness</td>
<td>( K_{D-F} )</td>
<td>MN/m</td>
</tr>
<tr>
<td>Drum-frame damping</td>
<td>( C_{D-F} )</td>
<td>kN·s/m</td>
</tr>
<tr>
<td>Soil stiffness</td>
<td>( K_s )</td>
<td>MN/m</td>
</tr>
<tr>
<td>Soil damping</td>
<td>( C_s )</td>
<td>kN·s/m</td>
</tr>
<tr>
<td>Vertical Excitation Force</td>
<td>( F_{ecc} )</td>
<td>kN</td>
</tr>
</tbody>
</table>

The lumped model was developed using Simscape (an extension of MATLAB™). This graphical programming environment enables the simulation of mechanical components and their response against dynamic loads in the time domain.

As shown in Figure 6, the soil mass, drum mass, frame mass, drum-roller contact mechanism, suspension systems, and compacted soil mechanical properties were modeled. The lumped parameter model developed in this document neglects any rotational or transversal motion that may occur in field operation during IC practices. The model only simulates vertical forces. Vertical motion records of the soil, drum, and frame are measured through virtual ideal translational motion sensors in Simscape.
3.2 Numerical Model

The development of the multi-degree of freedom lumped parameter described in Section 3.1 is based on the particular motion solutions of the mass components. The ideal translational motion sensors in the model provide the frame, drum, and soil displacements as $z_f$, $z_d$, and $z_s$, respectively. The frame is modeled to transfer forces to the drum through the drum-frame suspension system ($K_{D-F}$ and $C_{D-F}$). From the frame’s free body diagram shown in Figure 8, a relationship between the drum-frame suspension system and frame motion can be developed using

$$-K_{D-F}(z_d - z_f) - C_{D-F}(\dot{z}_d - \dot{z}_f) - m_f g = m_f \ddot{z}_f$$

(4)

$$-K_{D-F}(z_d - z_f) - C_{D-F}(\dot{z}_d - \dot{z}_f) = m_f \ddot{z}_f + m_f g$$

(5)
Figure 8. Free-body diagram of frame mass.

As shown in Figure 9, the drum transfers frame’s suspension reacting forces in addition to drum and soil static weights, vertical excitation force ($F_{ecc}$), and inertial mass to the spring-damper compacted geomaterial model. Eqs. 6-7 display the summation of vertical forces and solve for the soil spring-damper reacting force.

\[
K_s z_s + C_s \ddot{z}_s + K_{D-F} (z_d - z_f) + C_{D-F} (\dot{z}_d - \dot{z}_f) - (m_s + m_s)g + F_{ecc} = m_d \ddot{z}_d + m_s \ddot{z}_s \quad (6)
\]

\[
K_s z_s + C_s \dot{z}_s = -K_{D-F} (z_d - z_f) - C_{D-F} (\dot{z}_d - \dot{z}_f) + (m_s + m_s)g - F_{ecc} + m_d \ddot{z}_d + m_s \ddot{z}_s \quad (7)
\]

Figure 9. Free body diagram of drum attached the soil mass.
Drum-frame stiffness and damping coefficients can be replaced by frame mass and acceleration records by substituting Eq. 5 into Eq. 7. The reacting forces from the soil spring-damper pair result from adding static weights to inertial masses and subtracting the vertical excitation force, as shown in Eqs. 8 and 9.

\begin{equation}
K_s z_s + C_s \dot{z}_s = m_f \ddot{z}_f + m_f g + (m_d + m_s) g - F_{ecc} + m_d \ddot{z}_d + m_s \ddot{z}_s \tag{8}
\end{equation}

\begin{equation}
K_s z_s + C_s \dot{z}_s = \text{static weight} - \text{vertical excitation force} + \text{inertial masses} \tag{9}
\end{equation}

As shown in Figure 10, the force affecting the soil spring-damper pair is different than in Figure 9 during a loss of drum-soil contact. During the instant drum decouples from the soil element, the reacting soil spring-forces are affected only by the soil static weight and inertia, as shown in Eq. 10.

\begin{equation}
K_s z_s + C_s \dot{z}_s = m_s g + m_s \ddot{z}_s \tag{10}
\end{equation}

![Diagram of soil mass and forces](contact)

Figure 10. Forces acting on the spring-damper simulated soil during loss of contact.

The soil mass is modeled as an element attached to the soil spring-damper mechanism in permanent contact. Contact force \((F_c)\) is the sum of forces exciting motion in the modeled soil spring-damper mechanism. Soil mass adds to \(F_c\) even during loss of drum-soil contact, as shown in Eq. 11.

\begin{equation}
F_c = K_s z_s + C_s \dot{z}_s = \begin{cases} (m_f + m_d + m_s) g - F_{ecc} + m_f \ddot{z}_f + m_d \ddot{z}_d + m_s \ddot{z}_s & \text{(contact)} \\ m_s g + m_s \ddot{z}_s & \text{(loss of contact)} \end{cases} \tag{11}
\end{equation}
3.3 Drum-Soil Interaction

A translational hard stop was incorporated into the model to allow drum-soil decoupling. The translational hard stop is a mechanism that allows the drum to transfer dynamic loadings and to move independently from the surface of a simulated geomaterial, as shown in Figure 11a. As shown in Figure 11b, the translational hard stop allows the customization of lower and upper bound location, stiffness, and damping coefficients.

The hard stop parameter values are summarized in Table 4. The lower bound gap is defined as zero (no gap), and spring-damping coefficients at the lower bound are defined to have considerably large magnitudes (e.g., 10,000 times soil stiffness and damping coefficients) to neglect any influence of the hard stop properties in the calculation of the soil stiffness and damping. The upper bound gap is defined as infinite to enable the roller to decouple freely, and their spring-damping coefficients may be either ignored or defined as zero.

Figure 11. (a) Simple representation of Translational Hard Stop mechanism (b) Representation of components in Translational Hard Stop used in lumped model.
Table 4. Hard stop assumed parameters for roller-soil interaction simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bound</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness Coefficient</td>
<td>Upper</td>
<td>$k_{ub}$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>$k_{lb}$</td>
<td>10,000 $K_s$</td>
</tr>
<tr>
<td>Damping Coefficient</td>
<td>Upper</td>
<td>$c_{ub}$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>$c_{lb}$</td>
<td>10,000 $C_s$</td>
</tr>
<tr>
<td>Gap</td>
<td>Upper</td>
<td>$g_{ub}$</td>
<td>Infinite</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>$g_{lb}$</td>
<td>0</td>
</tr>
</tbody>
</table>

3.4 Model Behavior

For the continuous contact mode, the displacement of the geomaterial surface is the same as the roller’s drum displacement, as shown in Figure 12a. Displacements are positive downward and neglect the displacement due to settlement from the static weight of the roller. The difference between the drum and soil displacements is calculated and plotted to determine the drum-soil interaction mode, as shown in Figure 12b.

The drum-soil interaction is characterized as the loss-of-contact mode described in Figure 2 when resultants are greater than zero. Otherwise, the drum-soil interaction mode is continuous contact. As shown in Figure 12c, the contact force ($F_c$) is inverted to signify that a positive force corresponds to a downward movement. Hysteresis loops help visualize the development of contact force through periodic displacements. As shown in Figure 12d, an oval-like pattern represents a continuous contact drum-soil interaction mode.

The Fast-Fourier-Transform (FFT) method can be applied to the motion and contact force-time histories to obtain the amplitudes in the frequency domain. The determination of the displacements (Figure 13a) and contact force (Figure 13b) in the frequency domain facilitates understanding the characteristics of the interaction between the roller and the simulated surface of the geomaterial.
Figure 12. Sample model responses during continuous contact drum-soil interaction mode.

Amplitudes in the frequency domain indicate representative magnitudes of the absolute difference between the periodic crest (or trough) and its offset (i.e., the center of the signal). For instance, in Figure 12c, the contact force ($F_c$) oscillates between 40 and 125 kN, with an estimated offset of about 82.5 kN. This offset is associated with the static weight of the roller. Thus, the amplitude of $F_c$ is about 42.5 kN. The magnitude of this amplitude is seen as a peak in the frequency domain in Figure 13b.
Figure 13. Sample model responses during continuous contact drum-soil interaction mode in the frequency domain.

The magnitudes of the displacement and contact force due to the static weight of the roller must be added to the amplitudes calculated from the FFT operations to obtain the maximum displacement and maximum contact force, respectively. Similar to the drum displacement record in the frequency domain, soil displacement time history can be turned into the frequency domain, as shown in Figure 13c. Soil displacement in the frequency domain provides valuable information, especially when there is a loss of drum-soil contact.

During continuous contact interaction mode, the soil and drum displacement amplitudes are of equal magnitude, as seen in Figure 13a and Figure 13c. The amplitude of drum acceleration
in the frequency domain is shown in Figure 13d. The magnitudes of amplitudes of drum acceleration are essential for the calculation of CMV and CCV.

In each figure, a single peak amplitude corresponding to the roller frequency of operation is apparent. Both CMV and CCV would provide near-zero results during continuous contact mode due to the lack of amplitudes at harmonic or subharmonic frequencies. Therefore, the magnitudes of CMV and CCV are negligible during continuous contact mode.

An example of the soil-drum interaction when partial uplift occurs can be observed in Figure 14. Partial uplift mode generally occurs on stiffer geomaterials as compared to geomaterials that produce continuous contact mode with the same roller.

Figure 14. Sample model responses during partial uplift drum-soil interaction mode.
The decoupling of the drum from the soil displacements is seen in Figure 14a, indicating partial uplift. The loss of the drum-soil contact can be observed in Figure 14b as the periodic peaks in the differences between the roller and soil displacements.

A change in the sinusoidal pattern of the contact force is apparent at the same time the drum decouples from the soil, as seen in Figure 14c. The change in the slope may be associated with the drum's impact on the soil. As shown in Figure 14d, the hysteresis loop during the partial uplift mode displays a truncated oval-like pattern. The partial uplift may also cause the truncated section of the hysteresis loop (on the negative displacement end).

Figure 15 shows the frequency-domain responses associated with the pavement and roller operating condition causing partial uplift illustrated in the time-domain responses described in Figure 14.

The loss of contact between the drum and the geomaterial results in additional amplitude peaks in harmonic frequencies. As shown in Figure 15a and Figure 15c, the drum and soil displacement amplitudes differ. This difference is associated with the motion the drum experiences during the partial uplift. As observed in Figure 15b, contact force amplitude peaks at the fundamental and harmonic frequencies can be obtained during partial uplift. The additional peaks at harmonic frequencies, in Figure 15d, are used to calculate CMV and CCV values.

The simulated drum and soil responses under the double jump mode are presented in Figure 16. The loss of drum-soil contact is evident in Figure 16a due to the periodic drum-soil decoupling. However, the “double jump” impact of the roller can be particularly appreciated in Figure 16b when two different “jump” heights periodically occur. In addition, a drastic change in the slope of the contact force occurs concurrently at the moment the drum impacts the soil, as seen in Figure 16c. This change in slope varies depending on the magnitude of the maximum separation between
the drum and soil. As shown in Figure 16d, a pair of apparently concentric hysteresis loops seem to overlap. The magnitude of the maximum contact force is proportional to the maximum drum displacement.

Figure 15. Sample model responses during partial uplift drum-soil interaction mode.
Figure 16. Sample model responses during double jump drum-soil interaction mode.

As shown in Figure 17, multiple amplitude peaks are present in all spectra. The six amplitude peaks (shown in Figure 4) needed to calculate a CCV can be extracted from the acceleration spectrum in Figure 17d. As observed in Figure 17b, contact force amplitude peaks at the fundamental, harmonic and subharmonic frequencies can be obtained during “double jump” mode. The differences between the soil and drum motion can be observed in the magnitude of the amplitude peaks in Figure 17a and Figure 17c.

A periodic “multiple jump” interaction mode similar to the one shown in Figure 18 is observed in very stiff soils. As shown in Figures 18a and 18b, the loss of contact is considerably longer and more prominent in terms of time and decoupling distance, respectively, than in the
previously observed values in Figures 16a and 16b. Figure 18c suggests that multiple periodic contact force patterns occur simultaneously, resulting in overlapped hysteresis loops, as shown in Figure 18d.

![Diagram showing sample model responses during double jump drum-soil interaction mode.](image)

Figure 17. Sample model responses during double jump drum-soil interaction mode.
Figure 18. Sample model responses during “multiple” jump drum-soil interaction mode.

The motion and contact force records in the frequency domain display amplitude peaks at the harmonic and at multiple subharmonic frequencies, as shown in Figure 19. A significant difference between the soil and drum motion amplitudes can be observed in Figure 19a and Figure 19b. Such difference is attributed to a considerable amount of time the drum remains separated from the soil per oscillation. For example, Figure 19b and Figure 19d results provide amplitude peaks at 15, 22.5, 30, 37.5, 45, and 60 Hz when Figure 17b and Figure 17d only show amplitude peaks at 15, 30, 45, and 60 Hz. In addition, spectra displaying multiple harmonic and subharmonic frequencies, as seen in Figure 19d may provide drum acceleration amplitudes at frequencies not considered by the CCV or the CMV calculations.
Figure 19. Model behavior example with “multiple” jump drum-soil interaction mode.

The impact of neglecting those additional acceleration amplitude values at subharmonic frequencies is unknown with the currently available ICMVs. Therefore, CMV and CCV results on geomaterials stiff enough to show “multiple jump” behavior during IC operations might not represent the soil stiffness as those extracted from IC operations with continuous contact, partial uplift, or double jump interaction modes. Drum acceleration amplitude records in the frequency domain for different drum-soil interaction modes can be observed in Figure 20.

In summary, during continuous, a single acceleration amplitude peaks at the fundamental frequency of operation, as seen in Figure 20a. During partial uplift mode, there are amplitude peaks at harmonic frequencies (Figure 20b). Double jump mode generates amplitudes at multiples of half
the fundamental frequency (Figure 20c). Moreover, amplitude peaks at additional subharmonic frequencies are present during multiple jump mode, as observed in Figure 20d.

![Graphs showing drum acceleration in the frequency domain for different drum-soil interaction modes.](image)

**Figure 20.** Sample of drum acceleration in the frequency domain for different drum-soil interaction modes.

The following section departs from the numerical model displayed in current sections and proceeds to describe the estimation of the geomaterial mechanical properties, in terms of soil stiffness \(K_s\, \text{MN/m}\), and Elastic Modulus \(E, \text{MPa}\)
3.5 Extraction of Mechanical Properties

The mechanical properties calculation involves principally using the information related to the contact force and displacements generated during IC operations. Instrumenting soil to measure its acceleration during compaction is not feasible. Available drum acceleration records may be subjected to two different procedures to calculate soil stiffness: Secant Method and FFT method.

3.5.1 Secant Method

The secant method provides a result used by Bomag or Amman/Case to estimate soil stiffness (Mooney and Facas, 2013). As shown in Figure 21, this method calculates the slope of a line that starts at the center of the hysteresis loop and ends at the point of maximum drum displacement. The center of the hysteresis loop is assumed to be where the vibratory displacement is zero and the contact force equal to the static weight of the vibratory roller. The soil stiffness, $k_s$, is estimated from (Kenneally et al., 2015),

$$k_s = \frac{F_c(@MAX z_d)-F_c(STATIC)}{z_d(MAX)-z_d(STATIC)} \quad (12)$$

defined as the ratio of the difference of contact force at maximum displacement and static weight to the difference of their respective drum displacements.

![Figure 21. Conceptual representation of Secant Stiffness during (a) continuous contact and (b) loss of drum-soil contact (Mooney et al., 2010).]
The four hysteresis loops and the lines from which the secant stiffness values are estimated for the samples discussed in Section 3.4 can be observed in Figure 22. Table 5 summarizes the results of secant stiffness in the examples shown in Section 3.4 and provides percent error.

![Hysteresis Loops](image)

**Figure 22.** Contact Force – Displacement Hysteresis Loops: Samples generated by the same roller at different soil stiffness values.

**Table 5.** Comparison of secant stiffness results vs model stiffness values.

<table>
<thead>
<tr>
<th>Model Stiffness (MN/m)</th>
<th>Calculated Secant $K_s$ (MN/m)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>40</td>
<td>0.8</td>
</tr>
<tr>
<td>100</td>
<td>101</td>
<td>0.7</td>
</tr>
<tr>
<td>125</td>
<td>125</td>
<td>0.2</td>
</tr>
<tr>
<td>400</td>
<td>396</td>
<td>0.9</td>
</tr>
</tbody>
</table>
3.5.2 FFT Method

The Fast Fourier transform (FFT) consists of an algorithm that can transform a time-domain signal into a representation of signal amplitude in the frequency domain (i.e., a transition from Figure 12a to Figure 13a).

During IC, the roller operates at a known rotational frequency $\Omega$ (aka fundamental frequency). Therefore, the motion and contact force spectrums are expected to show maximum values at $\Omega$. Stiffness, in general, is defined as the amount of force required to generate a unit displacement. The calculation of FFT soil stiffness $K_s$ consists of the absolute value of the result of dividing the amplitude of contact force ($F_c$) by the amplitude of drum displacement ($z_d$), both in complex numbers at $\Omega$. Therefore, the “FFT” soil stiffness, $k_s$, is calculated from

$$k_s = \left| \frac{\text{FFT}(F_c)(@\Omega)}{\text{FFT}(z_d)(@\Omega)} \right|$$

where $\text{FFT}(F_c)(@\Omega)$ is the amplitude of contact force in complex numbers at the $\Omega$ (as seen in Figure 24), and $\text{FFT}(z_d)(@\Omega)$ is the amplitude of the drum displacement in complex cumbers at $\Omega$ (as shown in Figure 25).

For example, the amplitude of $F_c$ spectrum at $\Omega$ is 42 kN (Figure 23a) and the amplitude of $z_d$ spectrum at $\Omega$ is 0.89 mm (Figure 23b) during a continuous contact drum-soil interaction mode with a simulated geomaterial stiffness of 40 MN/m. Therefore, “FFT” soil stiffness $k_s$ results in 47 MN/m with a resultant relative error is 18%.

The magnitude of $F_c(@\Omega)$ varies depending on the simulated geomaterial stiffness and the drum-soil interaction mode, as shown in Figure 24a-d. The magnitude of $F_c(@\Omega)$ seems to increase proportionally to the simulated geomaterial stiffness value during continuous contact, partial uplift, and double jump modes, as seen in Figure 24a-c. Contact force amplitudes at subharmonic...
Figure 23. Contact force and drum displacement amplitudes during continuous contact mode.

Figure 24. Contact force spectrum for different drum-soil interaction modes.
frequencies resulted in higher values than at fundamental during multiple jump mode, as observed in Figure 24d.

Figure 25 shows the drum displacement spectrum for continuous contact, partial uplift, double jump, and multiple jump modes. Figure 25a shows the smallest drum displacement amplitude among all the displayed samples, and it also increases during the partial uplift mode, as shown in Figure 25b. The increments in displacement magnitude continue during double jump mode, as shown in Figure 25c. Finally, the multiple jump drum-soil interaction mode leads to a reduced displacement amplitude at the fundamental frequency (30 Hz) and higher amplitudes at other subharmonic frequencies, as seen in Figure 25d.

Figure 25. Drum displacement spectrum for different drum-soil interaction modes
A summary of the soil stiffness values obtained with the FFT method from the four examples discussed in Section 3.4 is listed in Table 6. The calculated FFT soil stiffness values differ more from the model stiffness values than the results obtained from the secant method. The error was above 17% in three out of the four examples. A percent error of 1% was obtained from the examples with a model stiffness of 100 MN/m.

Table 6. Comparison of FFT stiffness results vs. model stiffness values.

<table>
<thead>
<tr>
<th>Model Stiffness (MN/m)</th>
<th>Calculated “FFT” $K_s$ (MN/m)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>47</td>
<td>18</td>
</tr>
<tr>
<td>100</td>
<td>101</td>
<td>1</td>
</tr>
<tr>
<td>125</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>400</td>
<td>55</td>
<td>86</td>
</tr>
</tbody>
</table>

During IC practices, where only the drum acceleration data is collected, a method named Omega Arithmetic is applied to transform the drum acceleration data into drum displacement time records. However, drum displacement records differ from soil displacement records drum-soil interaction modes involving loss of contact. The variation between calculated “FFT” and input $K_s$ is expected to be associated with the different motions the soil and drum experience during the loss of contact.

As observed in Figure 26, the calculated “FFT” $K_s$ using the soil displacements (obtained from simulation) provide results closer to the input soil stiffness than those obtained using drum displacement records. Although calculating “FFT” $K_s$ with soil displacements records provides results proportional to the input $K_s$, this is not practical unless the roller can measure soil surface displacement during IC operations.
Once stiffness has been calculated by either secant or FFT method, it is of interest to estimate the modulus of such geomaterial. Therefore, the following section addresses modulus estimation considering the roller variables and resultant motion during compaction.

### 3.6 Estimation of Modulus

Lundberg (1939) introduced the following theoretical relationship between the soil stiffness, $k_s$, and soil modulus, $E$, for a drum resting on a homogeneous, isotropic elastic half-space:

$$ k_s = \frac{EL\pi}{2(1-v^2)\left(1.8864+\ln\left(\frac{L}{16R(1-v^2)F_c}\right)\right)} $$

(14)
where $L$ and $R$ are the length and radius of the drum, respectively, and $v$ is the soil Poisson ratio (a value of 0.3 was considered in this study). Lundberg’s equation can be used to convert soil stiffness values and drum motion responses into modulus.

Pavement designs and their geomaterial specifications are often modulus-based. Therefore, the extraction of modulus from calculated stiffness values enables the comparison of the results of the developed model with available standards.
Chapter 4. Sensitivity Analysis, Results, and Discussion.

This chapter aims to evaluate the impacts of the model variables in the estimation of CMV and CCV. This evaluation consists of a set of simulations of a specific vibratory roller operating on a geomaterial, in which a single roller or geomaterial property variable is modified at a time. Motion response, CMV, and CCV values are collected and analyzed from each simulation.

4.1. OAT Sensitivity Analysis Methodology

The sensitivity study developed in this chapter is based on the one-at-a-time (OAT) method. It consists of evaluating the results from changing the value of one input variable at a time. This study considers a standard vibratory roller as the reference roller. Table 7 provides a listing of the roller variables and their nominal values that are considered in the sensitivity study.

Table 7. Roller variable values for Sakai SV 510D

<table>
<thead>
<tr>
<th></th>
<th>Sakai SV 510 D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum mass</td>
<td>4,466 kg</td>
</tr>
<tr>
<td>Frame mass</td>
<td>2,534 kg</td>
</tr>
<tr>
<td>Soil mass</td>
<td>1,340 kg</td>
</tr>
<tr>
<td>Drum/Frame stiffness</td>
<td>1.27 MN/m</td>
</tr>
<tr>
<td>Drum/Frame damping</td>
<td>3.8 kN·s/m</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>30 Hz</td>
</tr>
<tr>
<td>Mass moment ($m_0e_0$)</td>
<td>4.21 kg·m</td>
</tr>
</tbody>
</table>

The roller-dependent parameters varied based on the information collected from over 30 commercially available rollers manufactured by Amman, Bomag, Case, CAT, Dynapac, Ingersoll Rand, Sakai, and Volvo, as summarized in Table 8.
Table 8. Parameter value ranges in commercially available vibratory rollers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum mass, kg</td>
<td>1,600</td>
<td>13,450</td>
</tr>
<tr>
<td>Frame mass, kg</td>
<td>1,650</td>
<td>5,450</td>
</tr>
<tr>
<td>Operation frequency, Hz</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Amplitude, mm</td>
<td>0.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Drum-Frame Stiffness, MN/m</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Drum-Frame Damping kN·s/m</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Drum width, m</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Drum diameter, m</td>
<td>0.7</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The calculation of CMV, CCV, $K_s$, and modulus followed the procedure in Chapter 3. Development of Lumped Parameter Model. Even though the drum width and diameter are not input values in the lumped model; they are exclusively used in this study for the estimation of soil modulus through the Lundberg equation (Eq. 14).

The sensitivity analysis contemplates sets of simulations of 200 cases in which a soil or roller parameter is uniformly distributed within the range shown in Table 8 while keeping constant the rest of the reference roller parameters, $K_s$, and $C_s$. Each set of simulations was repeated at five different $K_s$ values of 5 MN/m, 50 MN/m, 100 MN/m, 150 MN/m, and 200 MN/m to evaluate the impact of soil stiffness in CMV and CCV at different drum-soil interaction modes, except for the set of simulations that only varies input soil stiffness. The value of $C_s$ (kN·s/m) was calculated for every $K_s$ value using

$$C_s \approx 27 \cdot \sqrt{K_s}$$ \hspace{1cm} (15)

where $C_s$ is in kN·s/m and $K_s$ in MN/m. This $K_s$ to $C_s$ relation was established based on the results of a best-fit analysis with experimental data performed by van Susante and Mooney (2008).
The sensitivity study was organized in the following order. First, the soil stiffness was varied to evaluate the pattern of CMV, CCV, and modulus while maintaining the reference roller parameters constant. The value of $K_s$ is varied from 5 to 400 MN/m to identify relationships between the different drum-soil interaction modes and both CMV and CCV.

In the second study, $C_s$ was uniformly varied in a range of 50% – 150% of the result from Eq. 15 to evaluate the impact of fluctuation of soil damping in the motion response for the five selected soil stiffness, $K_s$, values (5, 50, 100, 150, and 200 MN/m). Third, the impacts of the fluctuations of the frame mass, drum mass, and soil mass were evaluated. Fourth, the influence of variations in the frame-drum suspension constants ($K_{D-F}$ and $C_{D-F}$) were evaluated. Finally, the impact of fluctuations in the operational frequency ($f$) and amplitude were evaluated. The reference roller parameters will be marked with a red bar in the following figures.

4.2 Geomaterial Mechanical Properties

4.2.1 Soil Stiffness

The variations of CMV, CCV, and modulus as a function of input soil stiffness are shown in Figure 27. Moduli obtained from Eq. 14 exhibit a linear proportionality to modeled soil stiffness. On the other hand, CMV and CCV are insensitive to changes in soil stiffness for values lower than 80 MN/m. From stiffness values of 80 MN/m to approximately 125 MN/m, an approximate linear relationship between CMV or CCV and soil stiffness is observed. A change of slope for CMV or CCV with soil stiffness is observed past a stiffness of 125 MN/m. The slope of the CCV trends toward a proportional increase with the soil stiffness until 400 MN/m.

On the other hand, CMV becomes inversely proportional to the soil stiffness in the range of 125-180 MN/m. Also, after a soil stiffness values greater than 180 MN/m, the CMV slope turns
back positive, as seen in Figure 27. The results indicate a complex dependency of CMV and CCV to $K_s$; therefore, further understanding of the amplitudes in the acceleration spectrum is required.

The drum acceleration amplitudes used for CCV and CMV calculations are plotted individually against $K_s$ in Figure 28. The amplitude at the fundamental frequency ($A_2$) displays the highest values, increasing proportionally to the soil stiffness value until approximately a $K_s$ of 120 MN/m; after which it starts decreasing slowly until an apparent “stable” value at a magnitude of approximately 34 m/s$^2$ is reached.

Figure 27. ICMVs (unitless) vs. modeled soil stiffness (MN/m)
Figure 28. Drum acceleration amplitudes vs. soil stiffness.

The magnitudes of \( A_4 \) and \( A_6 \) start increasing after a \( K_s \) of approximately 86 MN/m, signifying the threshold of the continuous contact interaction mode and the start of partial uplift mode. The magnitude of \( A_4 \) increases within a relatively short range of \( K_s \) (86–122 MN/m).

On the other hand, \( A_6 \) increases within a shorter range (86-100 MN/m) and remains constant until 122 MN/m. This stiffness value is also the initial \( K_s \) from which the magnitudes of \( A_1 \), \( A_3 \), and \( A_5 \) increase, indicating the start of the double jump drum-soil interaction mode. \( A_4 \) decreases from a \( K_s \) of 122 MN/m to approximately 180 MN/m indicating the complete range in which the drum-soil interaction mode is in double jump. The interaction mode for \( K_s \) greater than 180 MN/m is considered a multiple jump mode. When overlapping the drum-soil interaction mode thresholds in Figure 27, the interaction mode thresholds determined by analyzing the acceleration amplitudes match the slope changes for both CMV and CCV, as shown in Figure 29.
Figure 29. Drum-soil interaction modes on a CMV + CCV vs. modeled soil stiffness plot.

These results indicate potential proportionality between CCV and $K_s$ during partial uplift, double jump, and multiple jump drum soil interaction modes for the reference roller. CMV exhibits proportionality with $K_s$ during partial uplift and multiple jump interaction modes. An inversely proportional trend between CMV and $K_s$ during double jump mode (122-180 MN/m) is observed.

4.2.2 Soil Damping

The reference soil damping coefficient ($C_s$) values were calculated through Eq. 15 for five $K_s$ values (5, 50, 100, 150, and 200 MN/m). Then 200 simulations varying $C_s$ within a range of 50% to 150% of its reference value were performed for each $K_s$. The results from all cases were normalized with the corresponding values determined with the reference $C_s$.

As observed in Figure 30, the sets corresponding to $K_s = 5$ MN/m and $K_s = 50$ MN/m did not show a change in magnitude, indicating that the fluctuation of soil damping coefficient did not
modify the continuous contact interaction mode due to their near-zero values. On the other hand, for $K_s$ equal to 100, 150, and 200 MN/m, the CMV changed without apparent trends.

Figure 30. Impact of soil damping coefficient in CMV for five different soil stiffness values.

Figure 31 displays the variations of CCV with normalized $C_s$ for five different $K_s$ values. No fluctuation was observed for the two lowest $K_s$ values. For $K_s$ equal 100 MN/m, CCV results varied almost linearly from 8 to 21. In the case of $K_s$ equal to 150 MN/m, the values are relatively stable for $C_s/C_{s-ref}$ of 0.5 to 1.2. Finally, for $K_s$ equal to 200 MN/m, CCV only varied between 55 and 63 within all $C_s$ values considered. There are differences between the behavior of CMV and CCV when the soil damping constant varies. ICMV results fluctuations are more predictable for CCV than they are for CMV in most cases.
4.3 Static Weight

This section evaluates the impact of the static masses one at a time. Each set of simulations consisted of 200 cases in which the masses were perturbed within the range defined in Table 8.

4.3.1 Frame Mass

As shown in Figure 32, CMV does not change for the two lowest $K_s$ values. For $K_s$ of 100, 150, and 200 MN/m the behaviors differ from one to another within the range of frame masses considered. CMV stabilizes after frame mass with at least 4,500 kg for the five simulated $K_s$ values.

As seen in Figure 33, for $K_s$ of 200 MN/m, CCV does not fluctuate much for frame masses of 1,650 kg to 3,500 kg. Then, an abrupt decrease in CCV occurs between frame masses of 3,500 kg and 3,800 kg. For $K_s$ of 150 MN/m, similar behavior is observed, in which CCV remains constant after an abrupt decrement. CCV values are inversely proportional to the frame mass for a $K_s$ of 100 MN/m. For $K_s$ of 5 MN/m and 50 MN/m, CCV values are rather small and constant.
Figure 32. Impact of frame mass in CMV results for five $K_s$ values.

Figure 33. Impact of frame mass in CCV results for five $K_s$ values.
4.3.2 Drum Mass

As observed in Figure 34, there are no apparent changes in CMV for the two lowest $K_s$ values when the drum mass varies within the range established in Table 8. For all the other simulated $K_s$ values (100, 150, and 200 MN/m), the CMV shows a “zigzag” behavior between the CCV and drum mass. In those cases, CMV values tend to zero as the drum mass exceeds a certain value. Thus, a roller with a given drum mass will not reflect CMV values unless the soil achieves a specific stiffness through compaction.

On the other hand, CCV exhibits an inversely proportional pattern with the drum mass for a given soil stiffness, as seen in Figure 35. This is the only case in which $K_s = 50$ MN/m simulation CMV and CCV results deviate from near-zero values. This indicates that rollers with lighter drums are more sensitive to changes in low $K_s$ values than those with heavier drums and vice versa. The drum mass value in which each simulation reaches a near-zero value coincides with the values observed in Figure 34. Both Figure 34 and Figure 35 indicate the importance of the drum mass and its relevance in calculating CCV values and coinciding in the drum mass limit in which the system will become insensitive for a given soil stiffness value.

4.3.3 Assumed Soil Mass

The mass of soil has been modeled as a fraction of the mass of the drum. In this set of simulations, the soil mass varied from 0 to 60% of the mass of the drum, while keeping all the other parameters constant. The reference assumed soil mass during all simulations performed was 0.3 (30%) times the mass of the drum. As observed in Figure 36, the variation in CMV with the soil mass is dependent on $K_s$ (except for 5 and 50 MN/m that generate operations in continuous contact interaction mode).
Figure 34. Impact of drum mass in CMV results for five $K_s$ values.

Figure 35. Impact of drum mass in CCV results for five $K_s$ values.
Figure 36. Impact of soil mass in CMV results for five $K_s$ values.

Figure 37. Impact of soil mass in CCV results for five $K_s$ values.
On the other hand, CCV varies in an inversely proportional manner with the soil mass for $K_s$ values of 100, 150, and 200 MN/m, as observed in Figure 37. Again, the soft soils are not impacted by the variation in the soil mass.

4.4 Frame-Drum Suspension System

4.4.1 Frame-Drum Stiffness ($K_{D,F}$)

As observed in Figure 38, CMV values are mostly constant for $K_{D,F}$ values less than 2.5 MN/m. CMV maintains a constant value for $K_s$ of 5 MN/m, 50 MN/m, and 100 MN/m, independent of $K_{D,F}$.

![Figure 38. Impact of drum-frame suspension stiffness in CMV results for five $K_s$ values.](image)

The variations in CCV with $K_{D,F}$ in Figure 39 are rather constant up to a $K_{D,F}$ of about 4.5 MN/m. The impact of $K_{D,F}$ fluctuations seems minimal for CCV results in most cases. However, a drastic change in CMV and CCV for $K_s$ of 150 MN/m and 200 MN/m was observed at $K_{D,F}$ between 5.1MN/m and 5.4 MN/m.
Figure 39. Impact of drum-frame suspension stiffness in CCV results for five $K_s$ values.

4.4.2 Frame-Drum Damping ($C_{D-F}$)

As observed in Figure 40, CMV remains relatively constant as $C_{D-F}$ varies for all $K_s$ values. Some fluctuations are observed at the higher $C_{D-F}$ values. Similar trends are observed in Figure 41, for CCV. In general, both sets of simulations reflect the neglectable influence of $C_{D-F}$ in CMV and CCV results within the 2-12 kN∙s/m range.
Figure 40. Impact of drum-frame suspension damping in CMV results for five $K_s$ values.

Figure 41. Impact of drum-frame suspension damping in CCV results for five $K_s$ values.
4.5 Eccentric Mass System

4.5.1 Operating Frequency

As observed in Figure 42, the variations in CMV with the operating frequency ($f$) remained reasonably constant until an upper $f$ of 44 and 47 Hz for $K_s$ of 5 MN/m and 50 MN/m, respectively. Above those frequencies, CMV gradually increased with $f$. On the other hand, for $K_s$ of 100 MN/m, 150 MN/m, and 200 MN/m, CMV decreases inversely proportional to $f$ during the approximately 20-35 Hz range until reaching steady values.

CCV results are sensitive to variations in $f$, as observed in Figure 43. For $K_s$ of up to 100 KN/m, the trends of the variations in CCV with $f$ are similar to the variations of CMV with $f$. For $K_s$ of 150 MN/m and 200 MN/m, CCV values are constant with large dispersion up to $f$ of 40 Hz to 45 Hz.

![Figure 42. Impact of rotating frequency ($f$) in CMV results for five $K_s$ values.](image)

Figure 42. Impact of rotating frequency ($f$) in CMV results for five $K_s$ values.
Figure 43. Impact of operational frequency \((f)\) in CCV results for five \(K_s\) values.

### 4.5.2 Amplitude

The reference amplitude is considered as the resultant of dividing \(m_0e_0\) (eccentric mass moment) by \(m_d\) (drum mass), using the values provided in Table 7. In practice, the amplitude is inversely proportional to the operating frequency \((f)\) in compaction operations; therefore, operations are normally classified as “low-amplitude” (low \(A\) at high \(f\)) and “high-amplitude” (high \(A\) at low \(f\)).

As observed in Figure 44, CMV fluctuates significantly with the amplitude, except for the soils with \(K_s\) of less than 50 MN/m. The CCV values are also variable in a similar manner as the CMV values, as shown in Figure 45. There are two ranges of amplitude (0.5-0.75 mm and 0.8-1.15 mm) in which CCV slightly varies in amplitude.
Figure 44. Impact of operational Amplitude (A) in CMV results for five $K_s$ values.

Figure 45. Impact of operational Amplitude (A) in CCV results for five $K_s$ values.
Chapter 5. Summary and Conclusions

5.1 Summary

A lumped model that simulates intelligent compaction was developed in this study. The concept, numerical model approach, drum to soil contact interaction, and methodologies for extracting mechanical properties of geomaterials from model results are explained in Chapter 3. A one-at-a-time sensitivity analysis was performed to evaluate the impact of fluctuations of geomaterial properties and roller parameters in calculating IC measurement values CMV and CCV in Chapter 4.

5.2 Conclusions

The analysis of a simulated soil mass element supported by a spring-damper simulating the composite properties of a geomaterial subject to IC practices provided information to obtain specific and overall conclusions. The following conclusions can be made from the results of model development and the influence of soil and roller variations in calculating CMV and CCV.

1. CMV and CCV are sensitive to geomaterial mechanical properties $K_s$ and $C_s$. Both display specific trends at different $K_s$ and $C_s$ ranges that are associated with drum-to-soil interaction modes during IC operations.

2. An operation mode that involves loss of contact is necessary to obtain CMV and CCV with significant values.

3. A reduction in CMV is observed for $K_s$ values associated with the double jump mode, while CCV proportionally increased with $K_s$ in the range of values used in this study.

4. The masses of the frame, drum, and soil impact the CMV and CCV differently:
a. The CCV results displayed less variation than the CMV results due to the variation of the frame mass. Proportionality of CCV to $K_s$ was observed for frame mass, drum mass, and soil mass variations.

b. From the static masses, the variation of drum mass showed the highest impact in both CMV and CCV. The results indicate a relationship of $K_s$ to a range of drum mass values in which the roller is sensitive to CCV and a drum mass threshold in which a roller may become insensitive to $K_s$ changes.

5. The impact of drum-frame suspension system variables ($K_{D-F}$ and $C_{D-F}$) is negligible for CCV results. However, CMV results varied inconsistently with the variation of $K_{D-F}$.

6. The CMV and CCV results are more significantly impacted by the operating frequency ($f$) than other variables analyzed in this study. CCV results indicate proportionality to $K_s$ for a broader range of frequencies than CMV.

7. CMV and CCV display scattered results in certain amplitude ($A$) ranges. However, CCV results reflected proportionality to $K_s$ in a broader range (0.3 - 1.4 mm) than CMV (0.3 - 0.75 mm).

5.3 **Recommendation for Future Work and Research**

Additional research is required to understand the capabilities of IC practices further to estimate geomaterial properties during compaction. Further research is recommended in:

1. Evaluating the impact of simultaneous fluctuation of more than one variable at a time to detect interactions between roller variables.

2. Modeling permanent deformations and measuring motion responses with the mechanical properties of geomaterials.

3. Modeling layered geomaterials to characterize soil modulus per layer.
4. Validating simulated motion responses and extracted mechanical properties with information obtained during field IC practices.
References

Adam, D. (1996). *Flächendeckende dynamische Verdichtungskontrolle (FDVK) mit Vibrationswalzen (Continuous compaction control (CCC) with vibrating rollers)*


http://ascelibrary.org/doi/abs/10.1061/40940(307)80


https://doi.org/10.17226/25777


LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

CCC: Continuous Compaction Control
CMV: Compaction Meter Value
CCV: Compaction Control Value
QA/QC: Quality Assurance/Quality Control

$k_s$: Soil stiffness constant
$c_s$: Soil damping constant
$F_c$: Contact Force.
IC: Intelligent Compaction
g: Acceleration of gravity
$m_d$: Mass of roller’s drum
$m_f$: Mass of roller’s frame
$m_0 e_0$: Eccentric mass moment
$f$: Operational frequency (Hz)
$\omega$: Rotational speed (rad/sec)

$k_{D-F}$: Drum-Frame stiffness constant
$c_{D-F}$: Drum-Frame damping constant
$L$: Drum Length
R: Drum radius

$\nu$: Poisson ratio
$A$: Amplitude of drum motion.
$E$: Soil elastic modulus
ICMV: Intelligent Compaction Measurement Value

$A_\Omega$: Acceleration amplitude at fundamental frequency

$A_{2\Omega}$: Acceleration amplitude at the second fundamental frequency

$A_i$: $A_1, A_2, A_3, A_4, A_5,$ and $A_6$ are acceleration amplitudes at frequencies equal to 0.5, 1, 1.5, 2, 2.5 and 3 times the fundamental frequency, respectively.

$\Omega$: Fundamental frequency.
Appendix A

This appendix shows supplemental force and motion plots. The roller used for this Appendix was the Sakai SV 510 D vibratory roller and its characteristics are summarized in Table 7.

- Soil stiffness = 10 MN/m
• Soil Stiffness = 50 MN/m
Soil Stiffness = 100 MN/m
• Soil Stiffness = 150 MN/m
- Soil Stiffness = 200 MN/m
Vita

Jesús Castro Pérez was born in Monterrey, Nuevo León, Mexico in 1994. He joined the Universidad Autónoma de Nuevo León in 2011. During his undergraduate studies participated in international student competitions organized by the American Concrete Institute, studied a semester in Spain, and served as an intern at the Secretary of Economy of the State of Nuevo León. After obtaining an undergraduate degree in civil engineering moved to Chicago to work in a company that develops instrumentation for nondestructive evaluation of concrete. This experience ignited and nurtured my interest in concrete technology and nondestructive testing. In 2019 joined the University of Texas at El Paso and started a master’s degree program. During his studies, he served as a graduate teaching assistant for Dr. Ivonne Santiago. He wrote his master’s thesis under the supervision of Dr. Soheil Nazarian.

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