Influence of Rocking Motion on Vibratory Roller-Based Measurement of Soil Stiffness

Norman W. Facas1; Paul J. van Susante, A.M.ASCE2; and Michael A. Mooney, M.ASCE3

Abstract: Experimental data have shown that vibratory roller compactors often exhibit rotational kinematics in addition to translation during operation. This rotation is not considered in roller-integrated measurement systems that estimate soil stiffness based on drum vibration. To model and explore the effect of rotation, a lumped parameter roller/soil model was developed. The machine parameters for this model were tuned from suspended drum testing that isolated the drum from the ground. The model was then verified using field data collected over a range of excitation frequencies on spatially homogenous soil, and over transversely heterogeneous soil using one excitation position frequency. Rotational motion was found to significantly influence roller-integrated measurement of soil stiffness based on single position drum vibration data. Rotational motion causes single position measurement system results to be nonunique and to vary depending on the direction of roller travel. Using the model, various alternative measurement schemes were investigated. The directional dependence was eliminated by deriving a measurement at the drum’s center of gravity, and dual-sided measurement is proposed to gain a measure of heterogeneity. A more theoretical approach was also created wherein the contact force between the drum and soil are measured rather then being calculated.

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Introduction

Instrumented vibratory roller compactors are increasingly being used during earthwork compaction to assess soil properties [see Fig. 1(a)]. Research has demonstrated these rollers can discern changes in soil properties during compaction and provide a measurement of soil stiffness (Kröber et al. 2001; Anderegg and Kaufmann 2004; Mooney and Rinehart 2007; Rinehart and Mooney 2009). The potential for this so-called roller-integrated continuous compaction control (CCC) or intelligent compaction (IC) is significant in two ways. First, CCC can provide documentation of soil properties over 100% of the earthwork field [when combined with global positioning system (GPS) and documentation software]. This provides a dramatic improvement over current spot test approaches that assess less than 1% of prepared earthwork. Second, roller-based soil stiffness measurement is aligned with the philosophical shift toward field assessment of performance parameters consistent with mechanistic-based pavement design, e.g., modulus. Specifications for the use of CCC in earthwork compaction QA are currently in use in a number of European countries (e.g., Adam 2007) and are being developed and implemented in the United States (e.g., Minnesota Department of Transportation (Mn/DOT) 2007; Mooney et al. 2010).

Roller-based measurement of soil stiffness is based on the measurement of vertical drum vibration from accelerometer(s) mounted at a single drum location, typically at one end [see Fig. 1(b)]. The specific sensor locations vary across manufacturers and are dictated by access to nonrotating machine elements. The assumption in using single position sensors is that rotation about the x-axis [see Fig. 1(b)] of the drum (herein called rocking) is negligible. Under this assumption, previous research on roller vibration modeling has focused on vertical motion only (Yoo and Selig 1979; Adam 1996; Anderegg and Kaufmann 2004; Kopf and Erdmann 2005; van Susante and Mooney 2008).

Field assessment of drum kinematics in this study revealed that drum rocking is common, and is primarily due to soil stiffness heterogeneity beneath the drum. As an example, Fig. 2 illustrates roller-measured soil stiffness (kR) collected by driving a Sakai CCC roller [Fig. 1(a)] over a typical earthwork strip in opposite directions. Soil stiffness was computed from instrumentation installed by the writers using a previously published algorithm (Anderegg and Kaufmann 2004; Mooney and Rinehart 2007). As shown in Fig. 2, the kR based on a single-location accelerometer yielded occasional differences depending on the direction of roller travel, e.g., from x = 20–40 m. This difference in directional kR is attributed to drum rocking; the rocking was induced by independently verified soil stiffness heterogeneity.

This paper presents the findings from a study of rocking observed during vibratory rolling and its influence on roller-measured soil stiffness. A lumped parameter approach was employed to model the system based on successful modeling of less complex vibratory systems using this approach (e.g., Yoo and Selig 1979; Quibel 1980; Machet and Sanejouand 1980; Kröber


Fig. 1. (a) Vibratory roller compactor (Sakai); vibration created by eccentric mass within drum; (b) schematic of drum, coordinate system, and single-location acceleration measurement for estimation of soil stiffness.

The roller-soil model accounts for both vertical and rotational kinematics as well as commonly observed loss of contact (LC) between the drum and soil (Adam and Kopf 2004). This model is validated with field and laboratory data collected from a Sakai smooth drum vibratory roller [Fig. 1(a)] instrumented with accelerometers on both sides of the drum to capture vertical and rotational motion. The paper characterizes the potential error in single-location sensing and demonstrates that rocking should be considered in roller-integrated measurement of soil properties. Using the model, revised measurement approaches are explored to eliminate directional dependence and to provide some assessment of heterogeneity.

Model Development

A multidegree of freedom lumped parameter model was developed to capture translation and rocking motion of CCC rollers. This model consists of three main components, namely, the frame (f), the drum (d), and the soil (s) which is discretized into A segments, where a is any one component, to allow a varied stiffness profile along the drum [see Fig. 3(a)]. The displacements in the z-direction of the frame \( z_f \), drum \( z_d \), and soil \( z_s,a \) and the rotation of the frame about the x axis \( \theta_f \) and the drum \( \theta_d \) will be measured with respect to their centers of gravity (CG). Each CG has a mass \( m_f, m_d, m_s,a \) and the drum and frame each have a moment of inertia \( (I_f, I_d) \). Translation in the x and y directions will be ignored as they do not contribute to the determination of soil stiffness.

Vibration of the drum is induced by a rotating eccentric mass which generates an excitation force with vertical component \( F_{exc} = m_s,a \ddot{z}_s,a \sin \omega t \) at location \( y_d=0 \). Here, \( m_s,a \) is the eccentric mass moment and \( \omega \) is excitation frequency. The parameter \( m_s,a \) (and sometimes \( \omega \)) can be adjusted by the roller operator.

The drum is connected to the frame with B total connections. At any one connection b, the drum and frame are coupled by rubber isolation mounts modeled by linear elastic springs and linear viscous dashpots \( (k_f,b, c_f,b) \). The location of this connection is at \( y_{f,b} \) and \( y_{d,b} \), where all \( y \) coordinates are measured from the frame center of gravity (CG) and all \( y \) are referenced from the drum CG [see Fig. 3(b)]. The force from each rubber isolation mount \( F_{f,b} \) is given in Eq. (1)

\[
F_{f,b} = k_{f,b}[(z_d + \theta_d y_{d,b}) - (z_f - \theta_f y_{f,b})] + c_{f,b}[(\dot{z}_d + \theta_d \dot{y}_{d,b}) - (\dot{z}_f - \theta_f \dot{y}_{f,b})]
\]

Each soil segment is modeled as a viscoelastic material with mass \( m_s,a \), linear elastic stiffness \( k_s,a \), and viscous damping \( c_s,a \). Each segment is located at \( y_{s,a} \) measured from the CG of the drum. This simplified soil model was first introduced by Lysmer and Richart (1966) and is commonly used to model soil behavior in foundation vibrations and roller/soil modeling (Yoo and Selig 1979; Pietzsch and Poppy 1992; Anderegg and Kaufmann 2004; van Susante and Mooney 2008). Shear interaction between soil segments is neglected. The force generated by each spring-damper pair \( (F_{s,a}) \) is given by Eq. (2). The contact force between the drum and soil \( (F_{c,a}) \) is given by Eq. (3). The contact force has two different modes because a soil segment can be in contact or in LC with the drum [see Fig. 3(a)]

\[
F_{s,a} = k_{s,a} \ddot{z}_{s,a} + c_{s,a} \dot{z}_{s,a}
\]

\[
F_{c,a} = \begin{cases} \frac{F_{s,a}}{m_s,a} - m_s,a \dot{\theta}_s,a & \text{loss_of_contact} \\ 0 & \text{contact} \end{cases}
\]

Each CG has a mass \( m_f, m_d, m_s,a \) and the drum and frame each have a moment of inertia \( (I_f, I_d) \). Translation in the x and y directions will be ignored as they do not contribute to the determination of soil stiffness.

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\]

\[
F_{c,a} = \begin{cases} \frac{F_{s,a}}{m_s,a} - m_s,a \dot{\theta}_s,a & \text{loss_of_contact} \\ 0 & \text{contact} \end{cases}
\]
describes the behavior of the $a$th soil segment while in LC. While the soil is in contact, $F_{c,a}$ is dependent on $z_d$ and $\dot{\theta}_d$ as can be observed by substituting Eq. (8c) into Eq. (3) resulting in Eq. (10). Substituting Eq. (10) into Eqs. (6) and (7) and solving for $\dot{z}_d$ and $\ddot{\theta}_d$ results in Eq. (11) where $C$ is set of soil segments in contact with the drum. Eq. (11) can be used to model the drum for both the contact and LC case

$$m_j \ddot{z}_j = m_j g + \sum_{b=1}^{B} F_{f,b}$$

(4)

$$I_f \ddot{\theta}_j = \sum_{b=1}^{B} F_{f,b} y_{f,b}$$

(5)

$$m_d \ddot{z}_d = F_{ecc} + m_d g - \sum_{b=1}^{B} F_{f,b} y_{f,b} - \sum_{a=1}^{A} F_{c,a}$$

(6)

$$I_d \ddot{\theta}_d = F_{ecc} y_{ecc} - \sum_{b=1}^{B} F_{f,b} y_{f,b} - \sum_{a=1}^{A} F_{c,a} y_{a,a}$$

(7)

$$z_{s,a} = \dot{z}_d + \dot{\theta}_d y_{a,a}$$

(8a)

$$\ddot{z}_{s,a} = \ddot{z}_d + \ddot{\theta}_d y_{a,a}$$

(8b)

$$z_{s,a} = \dot{z}_d + \ddot{\theta}_d y_{a,a}$$

(8c)

$$m_{r,a} \ddot{\phi}_{a,a} = m_{s,a} g - F_{c,a}$$

(9)

$$F_{c,a} = \begin{cases} 0 & \text{loss of contact} \\ F_{s,a} + m_{s,a} \dot{z}_{s,a} + \ddot{\theta}_d y_{a,a} - m_{s,a} g & \text{contact} \end{cases}$$

(10)

$$\begin{bmatrix} \ddot{z}_d \\ \ddot{\theta}_d \end{bmatrix} = \begin{bmatrix} m_d + \sum_{a \in C} m_{s,a} + \sum_{a \in C} m_{r,a} y_{a,a} \\ \sum_{a \in C} m_{r,a} y_{a,a} I_d + \sum_{a \in C} m_{r,a} y_{a,a}^2 \end{bmatrix}^{-1} \begin{bmatrix} F_{ecc} + m_d g - \sum_{b=1}^{B} F_{f,b} - \sum_{a \in C} (F_{c,a} - m_{s,a} g) \\ F_{ecc} y_{ecc} - \sum_{b=1}^{B} F_{f,b} y_{f,b} - \sum_{a \in C} (F_{c,a} - m_{s,a} g) y_{a,a} \end{bmatrix}$$

(11)

$F_{c,a}$, $z_{d,a}$, and $\dot{z}_{s,a}$ are used to determine when the drum and soil are in contact. The $a$th soil segment loses contact when $F_{c,a} = 0$ and regains contact when $z_{s,a} = z_{d,a}$. When drum/soil contact occurs, $\dot{z}_{s,a}$, $\ddot{z}_d$, and $\ddot{\theta}_d$ must be modified to conserve linear and angular momentum. To do this, the impulse $j$ due to collision (assumed to be perfectly inelastic) must be computed using Eq. (12), where minus and plus superscripts represent the quantities before and after the collision, respectively. It is important to note that the impulse is based on the velocities at the impact point. The $\dot{\theta}_d^+$ and $\ddot{\theta}_d^+$ are given by Eqs. (13) and (14), respectively

$$j = -\frac{(\ddot{z}_d + \ddot{\theta}_d y_{s,a} - \ddot{\theta}_d)}{1/m_d + 1/m_{s,a} + (y_{s,a})^2 I_d}$$

(12)

$$\dot{\theta}_d^+ = \dot{\theta}_d + \frac{y_{s,a}}{I_d}$$

(13)

$$\ddot{\theta}_d^+ = \ddot{\theta}_d + \frac{j}{m_d} - \ddot{\theta}_d y_{s,a}$$

(14)

The model yielded an operational mode called double rocking, rocking at 0.5o, causing left-side/right-side alternating maximum amplitudes [Fig. 4(a)]. Double rocking mode was not observed in the experimental data but occurred in the model at high $k_r$. A rotational damper, $c_{rot}$, was added to the drum model to limit the unrealistic model response. Eq. (15) shows the modified Eq. (7). This damper was found to prevent the double rocking mode [see Figs. 4(a) and b] and had little effect when there was no double rocking present [see Figs. 4(c) and d]. The rotational damper represents a variety of soil effects resisting the rotation of the drum such as the increased surface contact area on the drum edges and soil stress hardening

$$I_d \ddot{\theta}_d = F_{ecc} y_{ecc} - \sum_{b=1}^{B} F_{f,b} y_{f,b} - \sum_{a=1}^{A} F_{c,a} y_{s,a} - c_{rot} \ddot{\theta}_d$$

(15)

**Model Validation**

The model was validated on a Sakai SV510D CCC roller with roller parameters provided in Table 1. In addition, one accelerometer was mounted on the left ($y = -0.853$ m) and another on the right ($y = 0.697$ m) side of the drum. The steady state model response was determined using a Dormand-Prince Runge-Kutta method with fixed time steps of 0.001 s. When an event occurred in the simulation (i.e., $F_{c,a} = 0$ or $z_{s,a} = z_{d,a}$), a bisection method was employed to determine the time of loss or gain of contact.
The steady state suspended drum model results are presented in Fig. 5(b). The model effectively captured the differences between left and right end acceleration due to rocking. However, the model accelerations were underestimated compared to the measured response [see Fig. 5(b)]. Several parameters were investigated to tune the model to the observed data. Due to the correlation of the machine parameters on the drum response only the drum mass \( (m_d) \) was adjusted from 4,466 to 4,126 kg. The suspended drum model with the adjusted mass matches the amplitude and left/right differences observed in the experimental data. The phase lag was also computed using the model [see Fig. 5(c)] and matches the experimental data.

**Frequency Response—Drum on Soil**

Low \( m_d\bar{e}_0 \) roller passes were performed over transversely homogeneous stabilized subgrade (USCS: SP-SM) soil. Seven excitation frequencies were employed \( (f=20.3, 23.6, 26.4, 29.5, 31.5, 33.1, \) and \( 20.7 \) Hz as shown in Fig. 6). The experimentally observed acceleration amplitudes are considerably greater than those observed during suspended drum vibration. Right-side drum acceleration exceeded left-side drum acceleration by 4–6%; this is greater than the 1–2% difference observed during suspended drum testing for low \( m_d\bar{e}_0 \) and \( f=20–35 \) Hz. The experimentally

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### Table 1. Roller Parameters for Sakai SV510D CCC Roller Provided by the Manufacturer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of drum ( m_d )</td>
<td>4,466 kg</td>
</tr>
<tr>
<td>Mass of frame ( m_f )</td>
<td>2,534 kg</td>
</tr>
<tr>
<td>Eccentric mass moment (low) ( m_0\bar{e}_0 )</td>
<td>4.21 kg·m</td>
</tr>
<tr>
<td>Frequency of ( m_0\bar{e}_0 ) ( f )</td>
<td>20–35 Hz</td>
</tr>
<tr>
<td>Stiffness of frame-drum mount ( k_{f,1} )</td>
<td>1,266 kN/m</td>
</tr>
<tr>
<td>Locations of mounts from frame CG ( y_{f,1} )</td>
<td>-0.992 m</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Moment of inertia of frame ( I_f )</td>
<td>1,696 kg·m²</td>
</tr>
<tr>
<td>Moment of inertia of drum ( I_d )</td>
<td>2,174 kg·m²</td>
</tr>
<tr>
<td>Eccentric mass moment (high) ( m_0\bar{e}_0 )</td>
<td>9.74 kg·m</td>
</tr>
<tr>
<td>Location of ( m_0\bar{e}<em>0 ) ( y</em>{d,dec} )</td>
<td>0.013 m</td>
</tr>
<tr>
<td>Eccentric mass moment ( \bar{e} )</td>
<td>0.013 m</td>
</tr>
<tr>
<td>Eccentric moment ( \bar{m} )</td>
<td>115.21 kN·m</td>
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<tr>
<td>Eccentric moment ( \bar{I} )</td>
<td>115.21 kN·m</td>
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<tr>
<td>Eccentric moment ( \bar{L} )</td>
<td>115.21 kN·m</td>
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<tr>
<td>Eccentric moment ( \bar{N} )</td>
<td>115.21 kN·m</td>
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<tr>
<td>Eccentric moment ( \bar{K} )</td>
<td>115.21 kN·m</td>
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<td>Eccentric moment ( \bar{M} )</td>
<td>115.21 kN·m</td>
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<td>Eccentric moment ( \bar{H} )</td>
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<td>Eccentric moment ( \bar{U} )</td>
<td>115.21 kN·m</td>
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<td>Eccentric moment ( \bar{T} )</td>
<td>115.21 kN·m</td>
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<td>Eccentric moment ( \bar{P} )</td>
<td>115.21 kN·m</td>
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<td>Eccentric moment ( \bar{R} )</td>
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<td>Eccentric moment ( \bar{X} )</td>
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<tr>
<td>Eccentric moment ( \bar{Y} )</td>
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</tr>
<tr>
<td>Eccentric moment ( \bar{Z} )</td>
<td>115.21 kN·m</td>
</tr>
</tbody>
</table>

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**Fig. 5.** Comparison of model response with experimental data from suspended drum testing: (a) suspended drum model; (b) peak drum acceleration versus excitation frequency; and (c) phase difference between drum displacement and excitation force.
The observed phase lag is much less than the near 180° phase of suspended drum vibration due to the presence of significant radiation damping (Mooney and Rinehart 2007) and the higher drum/soil resonant frequency.

The results from the LC rocking model, with \( k_s = 63 \text{ MN/m} \), \( c_s = 5.2/f \text{ MNs/m} \), and \( c_{rot} = 100 \text{ kNs/rad} \), fit well with the experimental data. The observed \( |\bar{Z}_d| \) and phase angles, as well as the difference in left versus right amplitude and phase, are captured by the model. The experimental data from the first \( f = 20.3 \text{ Hz} \) and last \( f = 20.7 \text{ Hz} \) passes suggest that the soil properties changed slightly during rolling, i.e., the \( |\bar{Z}_d| \) differed by 0.15 g and the phase by 3°. This process was not modeled; hence, the subtle differences in model fit for low versus high frequencies.

As an exercise to evaluate the importance of modeling the LC, the 4DOF full-contact rocking model was fit with the same parameters. This model was less effective at matching experimentally observed acceleration and phase (Fig. 6).

**Drum Acceleration Waveform Matching—Drum on Soil**

Low \( m_{dr0} \) roller passes were performed over a test area of stabilized subgrade (USCS: SP-SM) soil with transversely homogeneous and heterogeneous soil profiles. The transverse soil profiles \( (k_{sa} \text{ versus } y) \) were assessed using light weight deflectometer testing (e.g., Fleming et al. 2007) across the drum lane. Model response was fit to the experimental data in the time domain for one homogeneous and one heterogeneous soil stiffness profile (Fig. 7). The same \( k_{sa} \) profiles were used to model the left and right

![Fig. 6. Results of experimental and model vibratory drum response on transversely homogeneous soil: (a) amplitude; (b) phase](image_url)

![Fig. 7. Drum acceleration waveform matching between experimental and model response: (a) homogeneous transverse soil stiffness profile and left-side versus right-side experimental and model response; (b) heterogeneous transverse soil stiffness profile and left-side versus right-side experimental and model response](image_url)
sensor response. All other soil parameters were fixed: \( m_s = 0.1 m_p \), \( c_s = 150 \) kNs/m, and \( k_{rot} = 100 \) kNs/rad. Based on Fig. 7, the model is able to capture the difference between left and right sensor that are observed for experimental data for both profiles. There is an unmodeled high frequency effect in the experimental data, assumed to be caused by machine effects, e.g., engine vibration. This high frequency effect is not expected to affect \( k_{sR} \) computations.

**Influence of Sensor Location on Roller-Measured Soil Stiffness**

Commercially available CCC and IC rollers utilize vertical acceleration data from sensors mounted at a single drum location to estimate soil properties. This location varies across roller manufacturers. To investigate the influence of sensor location, low mass \( m_e \) model response to five different transverse soil stiffness profiles was examined. One homogeneous and four heterogeneous soil profiles were investigated [Fig. 8(a)], each similar to profiles observed experimentally using light weight deflectometer testing. Modeling involved five soil elements, with individual \( k_{sR} \) values varying across the drum length (total stiffness \( k_s = 55 \) MN/m).

The resulting \( |Z_d| \) for each stiffness profile is shown in Fig. 8(b) as a function of sensor location with respect to the drum CG. For both homogeneous and heterogeneous soil stiffness profiles, sensor location has a significant influence on \( |Z_d| \). Due to the asymmetry of the drum, the most homogenous profile \( |Z_d| \) does not correspond to the homogenous \( k_{sR} \) profile.

Roller-measured \( k_{sR} \) was computed using \( |Z_d| \) and knowledge of the position of the eccentric mass, and is shown versus sensor location in Fig. 8(c). The \( k_{sR} \) and \( k_{sR} \) differ by a factor of 5 because \( k_{sR} \) is composed of five springs in parallel, whereas, \( k_{sR} \) represents the total stiffness, i.e., \( k_s \). For Profile 3 (homogenous), \( k_{sR} \) can vary by up to 23% depending where the sensor was mounted. This is due to the asymmetry of the drum. For Profile 5 (most heterogeneous), \( k_{sR} \) can vary by up to 135%. Based on this, it is important to consider where the sensor is mounted, and that heterogeneity beneath the drum can have a large influence on the measurements.

**Directional Dependence of Roller Measurement Values**

Drum rotation and the resulting influence of sensor location on \( k_{sR} \) create a number of challenges for roller-measured stiffness. As mentioned in the introduction, roller-integrated CCC is increasingly being employed for quality assessment of earthwork compaction (e.g., Minnesota Department of Transportation [Mn/DOT 2007]; Adam 2007). A commonly used approach involves correlating \( k_{sR} \) to soil properties measured from in situ spot test measurements, e.g., density, modulus. With current single sensor measurement systems, the correlation between \( k_{sR} \) and spot test measurements would be dependent on roller travel direction and is not unique. Fig. 9(a) illustrates this point by presenting model results of roller-measured \( k_{sR} \) determined via simulation on a transversely heterogeneous \( k_{sR} \) profile derived from light weight deflectometer test results. In Fig. 9(a), \( k_{sR} \) was extracted from simulations of the roller vibrating on the underlying \( k_{sR} \) profile at multiple \( y \)-position offsets and in both roller travel orientations (into and out of the page). For each roller position and travel orientation, \( k_{sR} \) was determined and reported at two sensor locations illustrated in Fig. 9(a). The left and right \( k_{sR} \) data differ for each case evaluated. In addition, \( k_{sR} \) determined from a single sensor location is directionally dependent, i.e., at every \( y \) position, the open and closed squares or circles exhibit different results.

An improved measurement approach would produce a unique

**Fig. 8.** Influence of single sensor location on resulting drum acceleration and roller-measured soil stiffness: (a) five soil stiffness profiles each with five discrete \( k_{sR} \); (b) model peak acceleration as a function of sensor location; and (c) computed \( k_{sR} \) as a function of sensor location

**Fig. 9.** Relationship between roller-integrated measurement configurations and transverse soil stiffness. Roller-measured soil stiffness determined as follows: (a) single sensor-based \( k_{sR} \) from each drum end and reported at the location of the measurement; (b) \( k_{sR} \) determined from CG vertical vibration and reported at the CG; and (c) localized \( k_{sR} \) determined using localized contact force. All data collected from simulations of roller drum at multiple \( y \) offsets and oriented in both travel directions (into and out of page).
where \( k_{s,g} \) is the stiffness beneath the drum and \( F_e \) is the eccentric excitation force. The eccentricity \( ecc \) is estimated from the drum inertia \( F_{\text{inertia}} \) and the weight under the drum axle \( F_{\text{static}} \). However, if \( F_e \) could be determined, a more localized \( k_{s,R} \) (note the subscript to differentiate from \( k_{s,R} \)) could be estimated. Here, \( k_{s,R} \) is a local roller-measured stiffness and therefore provides an estimate of \( k_{s,R} \) rather than \( k_{s,g} \). In Fig. 9(c), estimated values of \( k_{s,R} \) are presented for various y offsets and for both travel directions. The computed \( k_{s,R} \) values are directionally independent and trend very well with the \( k_{s,g} \) profile. This approach allows the transverse heterogeneity in soil stiffness to be estimated in a robust directionally independent manner. The presentation of \( k_{s,R} \) is an academic exercise because the local contact force \( F_e \) cannot currently be measured. However, this analysis does shed light on the mechanics of soil stiffness measurement and what is required to enable the assessment of stiffness heterogeneity along the drum length

\[
F_e = F_{\text{inertia}} + F_{\text{ecc}} + F_{\text{static}} = m_0 g \cdot d + F_{\text{ecc}} + (m_d + m_l) g \quad (16)
\]

Conclusions

Vibratory smooth drum rollers exhibit rotational motion (rocking) when operating on both homogeneous and heterogeneous soil. A multidegree of freedom model was developed to predict the rotational kinematics of the vibratory roller during contact and LC motion. The model allowed for a distributed soil stiffness profile to mimic the transversely heterogeneous soil behavior observed in the field. A rotational damper was included to prevent a double rocking vibration mode not observed in the field data.

The model response was compared with data collected from a Sakai smooth drum vibratory roller with accelerometers mounted on each of the drum. Based on a comparison with this experimental data, the LC rocking model was able to capture the difference between left and right acceleration and phase that was observed over a range of soil stiffness profiles and operating frequencies.

Drum rotation resulting from commonly observed soil stiffness profiles was shown to significantly influence \( k_{s,R} \) derived from the single-location vertical drum vibration used widely in practice. Values of \( k_{s,R} \) were shown to vary up to 135% with sensor practice. \( k_{s,R} \) determined from single-location vertical drum vibration were found to be dependent on roller travel orientation, including on transversely homogeneous soil. Directional independence in \( k_{s,R} \) can be achieved by using vertical vibration data at the drum CG. This can be realized with vertical kinematics at two drum locations or vertical/rotational kinematics at one drum location. To estimate the transverse heterogeneity in soil stiffness within the drum length and maintain directional dependence, knowledge of the local contact force is required.

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References


