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Research Paper

Finite element analysis of vibratory roller response on layered soil systems

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ABSTRACT

The objective of this study is to quantify the relationships between continuous compaction control (CCC) roller soil stiffness measurements and subgrade and base lift moduli and thickness for quality control applications on fully compacted soils (e.g. proof rolls). This is done using plane strain, dynamic, time-domain finite element (FE) analyses. The FE model is calibrated against field data from two construction sites and is shown to capture the time-varying loading characteristics of the roller and the force–deflection behaviors of the underlying soil surface. The model is then used to explore the effects of subgrade and base moduli and the thickness of the compacted base layer on roller-measured stiffness values. The roller-measured stiffness increases with lift thickness and with subgrade and base moduli, showing sensitivity to both changes in lift thickness and in soil materials commonly observed in practice. The time-varying contact area is shown to have negligible effects on the roller-measured values. This observation is justified using a plane strain analysis of a layered elastic medium subjected to a dynamic strip loading.

1. Introduction

Continuous monitoring of soil compaction through roller measurements or continuous compaction control (CCC) has been used in the construction industry for over 30 years. By combining the roller-measured value (MV) (derived from drum accelerometer data) with onboard GPS measurements, the operator can perform real-time quality control (QC).

However, for CCC rollers to provide mechanistic measurements (e.g. individual layer Young's moduli (E_1, E_2), density (ρ), Poisson's Ratio (υ)) useful for engineering analysis and design, there must be a quantitative understanding of the roller/soil system and the roller MV. Historically, roller MVs have been used to gage soil compaction via relativistic measures: for example, the compaction meter value (CMV), utilizes the harmonic content of the drum acceleration and it was noted to increase with increased compaction [1]. More recently, roller MVs have been used to define absolute measures of soil stiffness, (k_s), variously defined by individual roller manufacturers (e.g., [2–5]). Vibratory drums provide a measure of k_s that reflects a composite nature of the underlying layers [6–8,4,9] for most earthwork construction situations (Fig. 1). The composite nature of k_s has led researchers to investigate potential relationships between roller-measured stiffness and individual layer moduli values [10–13] to allow for a more mechanistic relationship to CCC.

The relationship between k_s and in situ soil response is complex. Experimental data [14–16,3,17] have shown that roller/soil interaction is highly nonlinear and dependent upon the inertial and dissipative properties of the soil, based on the vibration frequencies employed (20–35 Hz). It involves transient response with time-varying loading conditions, including decoupling between the drum and soil, chaotic behavior, and drum and frame rocking [18–20]. The drum/soil contact area ($2a$) changes throughout each cycle of vibration from a maximum area to a minimum area, which can be zero if loss of contact is experienced. The literature has clearly conveyed $2a$ has a strong influence on stress/strain distributions within homogenous bodies [21–22] and layered systems [23–24,9]. A simple analytical analysis is performed to determine whether or not this behavior needs to be explicitly modeled.

The majority of the published literature on vibratory drum–soil mechanics is based on the analysis of lumped parameter models [25–26,17,27] and cone models [14,28]. Although van Susante and Mooney [17] are able to capture the decoupling between the drum and soil, and drum/frame rocking, and Rich [27] models a

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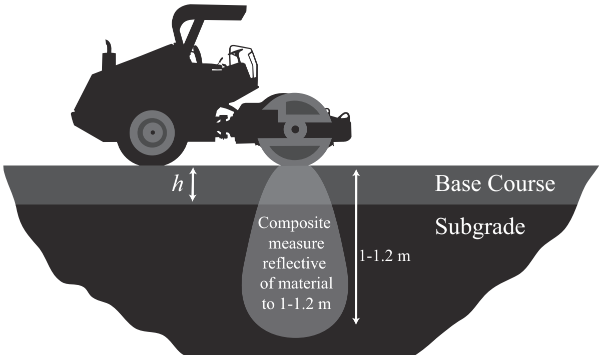

Fig. 1. Measurement depth of vibratory roller.

two-layer system, these aforementioned models are limited due to their inability to accurately model the inertial and dissipative properties of the soil. Since mass-spring-dashpot elements are used to describe both the roller and the soil, analysts using these models must "guess" at the inertial involvement via added masses. The elastic springs and dashpots cannot capture the continuum nature of the material (they have been successful in one-layer applications, e.g., Lysmer's analog [29], but have not been proven for multi-layer applications).

Multiple continuum based forward models have been developed to explore the influence of surface loads and soil parameters on system response. Although plane strain dynamic, elastic analytical models exist for strip loading on the surface of a half-space [22], none exist for a 2-layer system. The majority of published literature on elastic half-space, 2-layer or N-layer systems uses either axisymmetric [30–33] or three-dimensional modeling techniques [34–37]. In the above analytical models, a contact pressure distribution and $2a$ must be assumed, as the drum cannot be explicitly modeled. As a result, a constant $2a$ must be assumed throughout loading and loss of contact cannot be modeled.

The variable contact force during each cycle, combined with the dynamics and the multi-layer continua preclude the adoption of analytical solutions to describe the roller–soil system. As a result, discretized computational approaches must be used to capture the complex behavior. Dynamic elastic [10,38] and elasto-plastic FE models [39–41] have been developed that are able to capture the deformation directly below the roller. Erdmann et al. [39] show the importance of dynamics in roller response but focus their analysis on modeling different types of roller excitation and do not explore the relationship between measurable drum response and layer properties. Mooney et al. [10] and Mooney and Facas [38] provide preliminary analysis on individual layer parameter sensitivity for the FE model, but their focus is on the inversion process and on sensitivity analysis of a pseudo-static BEM model. None of the above FE models examines or addresses how the contact area is modeled and its influence on results. A thorough examination of the effects of time-varying contact area on drum response, and of roller MV sensitivities to underlying soil parameters, is needed to gain a truly mechanistic understanding of the system. To do this a robust forward model is needed that captures the dynamic loading conditions of the drum in addition to the inertial and dissipative properties of the soil.

In this paper we present the results of a study to model vibratory drum-layered soil interaction using dynamic finite element analysis. A main motivation for this study is to capture the time varying loading conditions of the system. Varying loading conditions created by curved drum interaction with the ground and decoupling of the drum from the ground are modeled. Using a kinematic contact algorithm, no assumptions need to be made regarding contact, allowing for a more physically accurate contact model. The FE model is calibrated and validated with experimental data from vertically homogenous and two-layer conditions and use the FE model to parametrically explore the relationship between vibratory roller response and system parameters such as elastic moduli and layer thickness. U.S. earthwork construction currently performs QA on a per lift basis (typically 15–30 cm). For each layer of earthwork (and the existing base), the roller creates a spatial map of MV data and of lift thickness. These data for the existing base or subgrade and each subsequent lift can be combined with this forward model, using an inversion program (per [38]), to extract individual layer moduli. This can be done simply by first performing the inversion process on the subgrade to find E_1. Once E_1 is known, we can find the subgrade modulus (E_2) from E_1 and h using inversion (a full description of this process is provided in [38]). The interpretation of the results from this forward finite element model provide a foundation for the mechanistic interpretation of the composite roller-measured stiffness for the individual dynamic mechanical properties of the underlying soil layers.

2. Background

2.1. FE model

2.1.1. Roller parameters and quantification of soil stiffness

Smooth drum vibratory CCC/IC rollers are nominally in the 12–15 metric ton range with drum diameters of approximately 1.5 m and drum lengths of approximately 2.1 m. Excitation is created by uni-directional or counter-rotating eccentric masses, $m_{o,}$ located at effective moment arms of e_o within the drum (see Fig. 2); magnitudes of eccentric mass moment, $m_o e_{o,}$ can range from 0 to 5.0 kg m, and excitation frequencies, Ω, can range from 25–35 Hz. In this study, we validate our finite element model with experimental data from a Sakai SV510D roller and accordingly summarize the key roller properties in Table 1.

Fig. 2a illustrates the lumped parameter mechanics of the vibrating drum. In this analysis geomechanics conventions are used, where the $+z$ direction points from the drum toward the ground (per Fig. 2). It is commonly assumed that the drum behaves as a rigid mass with a single vertical degree of freedom, z_d. Since the drum is modeled as a rigid mass, z_d corresponds to the vertical deflection of the soil surface when in contact. The drum is connected to the roller frame via low stiffness rubber isolation mounts. The weight of the frame on the drum is considered; however, for soil rollers, the influence of frame dynamics on the drum is insignificant [2] and thus is commonly neglected. To estimate a measure of composite ground stiffness k_s, the position of the eccentric mass-

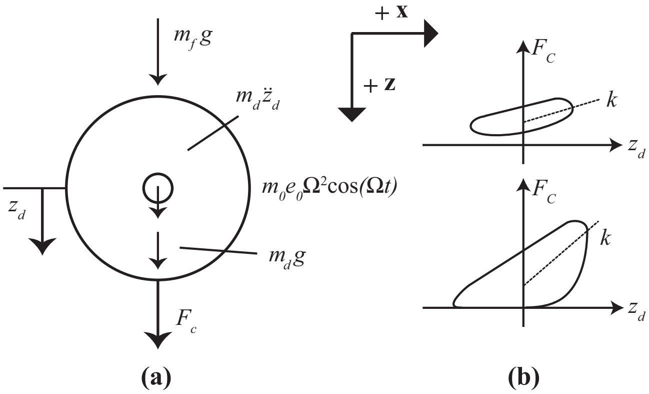

Fig. 2. (a) Free body diagram of vertical forces acting on drum. (b) Contact force vs. drum displacement response and resulting dynamic stiffness measures.