# Monitoring Roller Vibration During Compaction of Crushed Rock

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**ABSTRACT:** Real-time monitoring during soil compaction can be made possible by utilizing the vibration signature of a vibratory roller compactor. The compactor and soil constitute a coupled dynamic system, albeit complex and nonlinear. As the soil density increases and its mechanical properties change, the dynamic response of the compactor will change. Developing a thorough knowledge of the relationship between compactor vibration and soil properties has the potential to enable real-time monitoring of desired mechanical soil properties (e.g., resilient modulus) and subsequently intelligent compaction, wherein the forcing amplitude and vibration can be varied to optimize the compaction process. This paper presents the results of vibration monitoring during roller compaction of crushed rock (well-graded sand). Vibration monitoring revealed that drum vibration amplitude is mildly sensitive to increase in underlying material stiffness. Harmonic content, reported as total harmonic distortion, increased with greater sensitivity as the underlying soil densified and stiffened.

**KEYWORDS**: Soil Compaction, Health Monitoring, Soil Vibration, Soil-Machine Interaction.

## 1. INTRODUCTION

Vibratory compaction of geomaterials via plate, tamper, or drum roller is a widely accepted soil improvement method used to achieve the target density (e.g., standard or modified Proctor) and thus the mechanical properties (i.e., resilient modulus, shear strength) of the medium. The significant dynamic forces created by eccentric vibration at frequencies up to 60 Hz exceed the static forces by factors up to five and thus provide the necessary shear stress and acceleration levels to densify and improve the properties of geomaterials.

The proliferation of intelligent systems, prompted by the availability of technology and the desire for improved performance and efficiency, has begun to permeate transportation earthwork construction (e.g., autonomous construction field operation via GPS navigation and GIS mapping). The ability and cost efficiency of sensors, on board micro-processing, and wireless transmission makes feasible intelligent systems that can *sense* their environment and *adapt* to improve performance. Currently, vibratory compaction practice in the U.S. does not utilize the sensing and adaptation inherent in intelligent processes. Real time assessment is not integrated into the compaction operation; rather, the only quality assurance and quality control (QAQC) measures are performed independently at discrete locations that amount to well under 1% of the total area being compacted. Hence, compaction practice remains crude, labor-intensive and time-intensive. Soil compositions and behavior vary greatly even within a single construction job. Current practice requires that site-specific compaction guidelines (e.g., target moisture content and density, required number of passes) must be determined for each soil composition through extensive calibration by skilled technicians. An operator guides a compactor at a discretionary forward velocity over thin lifts of soil. The magnitude and frequency of the dynamic force (via eccentrics within the drum) are typically pre-determined and remain constant during operation. QAQC specifications require frequent verification of density and water-content, generally by a nuclear density gage-certified technician. The lack of integration between the compaction process and QAQC leaves costly under- and over-compacted areas.

The shift towards performance-based construction specifications places the onus on the designers and contractors to provide a product that will perform throughout its intended life (e.g., warranties). Performance-based compaction requires the deliverance of mechanistic soil properties (e.g., resilient modulus, shear strength, permeability) rather than the surrogate density and moisture content alone.

The use of vibration data to interrogate the health or condition of systems (e.g., machinery, structures) is part of the growing field of study of structural health monitoring [1]. The effective use of a compactor's vibration characteristics to assess the mechanical properties of the involved soil constitutes a form of continuous quality control or health monitoring. To develop performance based intelligent vibratory compaction techniques via vibration monitoring, a great deal must be learned about the response of the coupled compactor-soil system and the relationship between compactor and soil response. While on-board “compaction meters” that monitor drum vibrations are gaining acceptance in practice [2,3], the knowledge base surrounding the relationship between compactor vibration behavior and soil condition is not well developed.

The coupled compactor-soil system is nonlinear and pseudo-transient. There is little published data regarding the relationship between compactor and soil vibrations, the effect of frequency and amplitude on soil and compactor vibrations, and the nature of nonlinear soil behavior when subjected to vibratory compactor loading [4,5]. Previous studies of plate compaction have illustrated a relationship between vibration amplitude and level of compaction [6]. This research also revealed consistent trends in the evolution of harmonic content with soil compaction [6]. This paper presents some findings observed during monitored vibration on crushed rock test beds, with feature extraction from time and frequency domains. The results focus on drum and frame vibration amplitudes as well as harmonic content arising from the nonlinear system response.

## 2. EXPERIMENTAL SETUP

The test procedure is briefly described below; see [7] for a complete description. An Ingersoll-Rand Corporation SD-100D smooth drum (2.1 m wide, 1.5 m diameter) roller was used during the investigation (see Fig. 1). The SD-100D has an operating weight of 101-kN and a drum weight of 36-kN. Rotating eccentrics within the drum create the vibration force. Vibration frequencies range from 10 to 40 Hz; the vibration force can reach 200-kN under low amplitude settings. Depending on the soil properties, this can cause decoupling (bouncing) between the drum and ground. The roller drum and frame were instrumented with Summit Instruments (Akron, OH) and Crossbow (San Jose, CA) triaxial accelerometers aligned to measure vertical and horizontal (2 directions) acceleration. The low noise (5-10 mg rms), high sensitivity (200-420 mV/g) accelerometers measured drum and frame acceleration within a range of ±10 and ±7.5g, respectively. Acceleration data was sampled at 1 kHz and collected via a 16-bit National Instruments™ DAQ-card and laptop computer. Both time domain and frequency domain analysis were performed on the drum and frame acceleration data to explore the sensitivity of various signal features to the soil compaction process.


*Figure 1. Ingersoll-Rand Vibratory Drum Roller*

The results of compaction tests performed on well-graded sand (termed “crushed rock”) are presented in this paper. The instrumented vibratory roller was driven over 10-m long by 7-m wide soil beds carefully prepared with tilling equipment to prepare homogeneous loose soil typical of an earthwork construction environment. The soil beds were each prepared by tilling an approximately 300-mm thick soil lift to a homogeneous state. The subsurface beneath the crushed rock (CR) lifts was extremely stiff compacted gravel that served as a staging area for dump trucks, graders and loaders. Once the soil was tilled to a homogeneous loose state with the desired water content, a single pass of the compactor was performed (see Fig. 2). The forward velocity of the compactor was held constant at 0.5 m/s; however unavoidable variations in forward velocity did occur. Density, moisture content, and dynamic cone penetration testing were then conducted at two marked bed locations, 25% and 75% along the length of the bed. The dynamic cone penetrometer (DCP) was used to assess soil stiffness and strength (see Fig. 2). The impact force from a free-falling weight drives a DCP tip into the ground. The resulting dynamic penetration index (DPI) is defined as the amount of penetration (cm) per hammer blow. DPI has been correlated to resilient modulus and shear strength of soil [8]. This process of rolling and testing was repeated until the desired state was achieved (typically 5-8 passes).

*Figure 2.Operation of Roller on Test Bed with Staked Locations for Soil Property Measurement with Nuclear Density Gage (bottom left) and Dynamic Cone Penetrometer*

## 3. TEST RESULTS

Vibration was monitored during the compaction of three crushed rock test beds – CR1, CR2 and CR3. Vibration frequencies for the three tests ranged from 20 to 28 Hz. At the 25% and 75% marks, 2-second data files were extracted from each full-pass data file. Given the forward velocity of 0.5 m/s; each data file was consistent with 1-m of machine travel. Figure 3 illustrates the drum and frame acceleration amplitudes in the vertical and horizontal directions at the 75% mark during passes 1 (partially compacted) and 5 (compacted) on test bed CR1. Peak amplitudes of drum and frame acceleration in both the vertical z (upward and downward) and horizontal x (forward and aft) directions are presented. Positive values indicate upward and forward acceleration while negative values indicate downward and aft acceleration. Each data set is presented at a similar scale to allow visual comparison. The eccentric mass assembly rotates in a forward direction (i.e., with the same trajectory exhibited by the drum rotating as it would move forward); therefore, the xz-diagrams are produced by clockwise motion.

Figure 3 illustrates the consistent trends observed during compaction: (1) downward drum acceleration exceeds upward drum acceleration; (2) drum acceleration amplitude increases as the underlying medium stiffens. The drum acceleration depicted in Figure 3 undergoes significant change from pass 1 to pass 5 – increasing acceleration in both vertical and horizontal directions. It should be noted that the vibration frequency did increase from approximately 23 Hz during pass 1 to 25 Hz during pass 5; and hence, contributed somewhat to the increase in acceleration amplitudes.

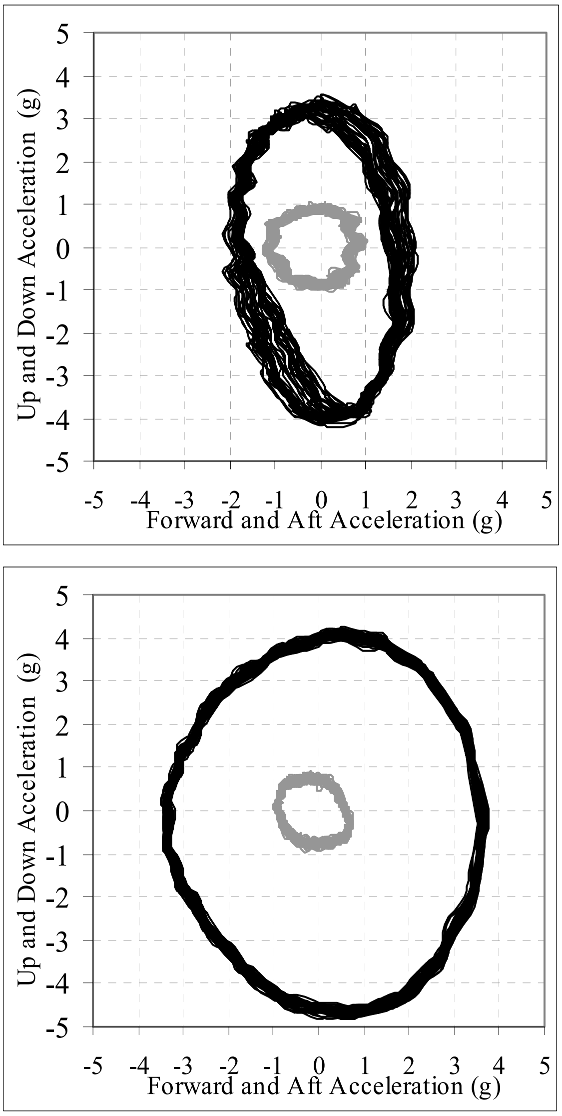


*Figure 3. XZ Drum (black line) and Frame (gray line) Acceleration Amplitudes During Vibration on CR1 Pass 1 Partially Compacted Soil (top) and Pass 5 Compacted Soil.*

Vertical drum acceleration amplitudes are plotted versus DPI for each CR bed in Figure 4. Though there is considerable scatter in the data, Figure 4 reveals a general trend wherein the drum acceleration increases as the DPI decreases (and the soil stiffens). During compaction of crushed rock, the downward drum acceleration was much greater (up to 50%) than the upward drum acceleration. Down acceleration amplitudes also exhibited less scatter. The vibration frequency also varied considerably within passes of the compactor and from pass to pass. To remove this variability due to vibration frequency, peak-to-peak acceleration amplitudes were normalized by the vibration force. The resulting normalized drum accelerations ($\bar{a}_{z(p-p)}/F_{vib}$) are presented in Figure 5. Figure 5 illustrates only a mild increase in normalized acceleration amplitudes with underlying stiffness. These results are consistent with findings during compaction on other sand sites [9].

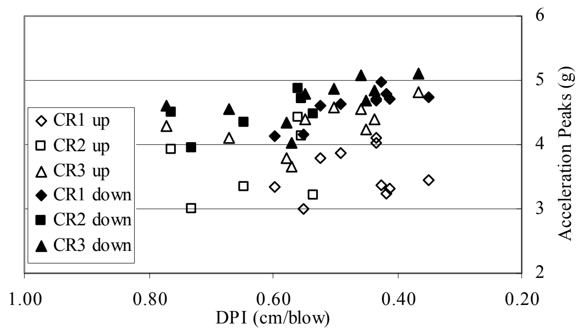


*Figure 4. Vertical Drum Acceleration Amplitudes During Compaction on Crushed Rock Test Beds*

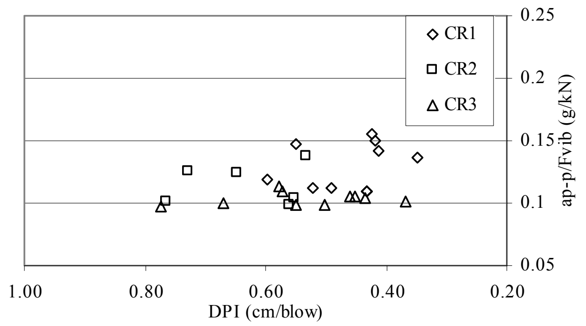


*Figure 5. Normalized Vertical Drum Acceleration Amplitudes During Compaction on Crushed Rock Test Beds*

The nonlinearity of the coupled roller compactor/underlying media system distorts the output of a sinusoidal input forcing function. The distortion is manifested in harmonic content within the drum and frame vibration data.

Frequency domain analysis of the vibration data was performed via FFT to investigate harmonic content as a measure of system nonlinearity. FFT analysis was performed on the two-second data files recorded at the 25% and 75% marks for each pass over test beds CR1-CR3. The frequency content was assumed to be constant during each 1-m long, 2-second interval. Harmonic amplitudes $A(f_i)$ were tabulated, where $A(f_1)$ is the amplitude of the fundamental (operational) frequency, $A(f_2)$ is the 1st harmonic amplitude (2 x fundamental frequency), etc. The total harmonic distortion (THD) provides a measure of collective harmonic content. THD is defined as:

$$\mathrm{THD} = \frac{\sqrt{A(f_2)^2 + A(f_3)^2 + \ldots + A(f_N)^2}}{A(f_1)} \times 100 \qquad (1)$$

Values of $A(f_3)$ through $A(f_N)$ were found to be insignificant compared to $A(f_2)$; hence, the THD essentially reflects the ratio $A(f_2)/A(f_1)$. THD values observed during compaction of crushed rock test beds are presented in Figure 6. Though scattered, the THD values increased from 8-18% during compaction of crushed rock beds.

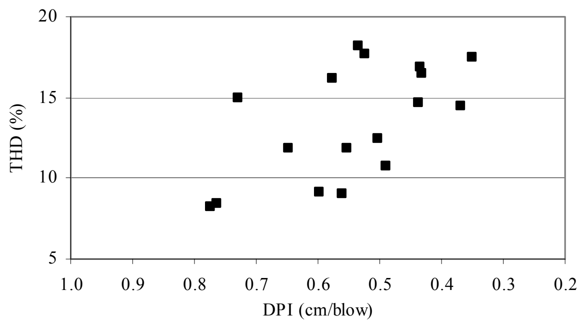


*Figure 6. Total Harmonic Distortion During Compaction of Crushed Rock*

## 4. SUMMARY AND CONCLUSIONS

To monitor vibration during compaction, the drum and frame of an Ingersoll-Rand compactor were instrumented with accelerometers. Vibratory compaction was carried out on carefully prepared beds of crushed rock to explore vibration characteristics and changes therein as the soil stiffens during compaction. Time-domain drum and frame acceleration amplitudes were fairly insensitive to changes in underlying material properties. During soil compaction, normalized drum acceleration values increased slightly (less than 10%) as the DPI more than doubled.

Harmonic content, measured during vibration and expressed as normalized frequency components and THD, exhibited greater sensitivity to changes in underlying material properties. THD essentially doubled during compaction of crushed rock.

These test results provide some promise for the effective use of real time monitoring of soil compaction. However, machine sensitivity to changes in soil properties during compaction was found to be subtle. Operational variability issues present a challenge to vibration based soil compaction monitoring. Fluctuations in vibration frequency, forward velocity, local variability in soil moisture and composition, and depth and stiffness of underlying strata all effect vibration characteristics. Machine variability can be addressed via control technology; however, the analysis techniques will have to be further developed to minimize the unavoidable soil variability.

## 5. ACKNOWLEDGEMENTS

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