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Roller-Integrated Compaction Monitoring Technology: Field Evaluation, Spatial Visualization, and Specifications

David J. White, Pavana K. Vennapusa, and Gieselman, Heath
Dept. of Civil Construction and Environmental Engineering, Iowa State University, Ames, Iowa, U.S.A.

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ABSTRACT: Roller-integrated compaction monitoring technologies provide virtually 100-percent coverage of compacted areas with real-time display of the compaction measurement values. Although a few countries have developed quality control (QC) and quality assurance (QA) specifications, broader implementation of these technologies into earthwork construction operations still requires a thorough understanding of relationships between roller measurement values and traditional in-situ spot test compaction measurements. The objectives of this paper are to (a) present field measurements from the vibratory-based Compaction Meter Value (CMV) and the vibratory or static rolling resistance based Machine Drive Power (MDP) monitoring technologies, (b) provide example correlations and spatial comparisons developed between roller measurement values and in-situ spot test measurements, and (c) summarize selected international specifications to highlight some of the key specification parameters and provide some practical points for successful implementation of the technologies.

1 Introduction

Roller-integrated compaction monitoring technologies (e.g. intelligent compaction or continuous compaction control) for vibratory rollers was initiated some 30 years ago in Europe for compacting mostly granular soils (e.g., Forssblad, 1980; and Thurner and Sandström, 1980) and has since been a subject of international discussion. There are different manufactures of vibratory-based technologies that make use of accelerometers mounted to the roller drum to effectively create a record of machine-ground interaction. The analysis approaches have been explained in detail by others (e.g., Adam and Brandl, 1997; and Sandström and Pettersson, 2004). Recently, a new machine measurement technology has been developed for use in granular or cohesive soils and is based on the principal of rolling resistance due to drum sinkage. The approach has the advantage of working in both vibratory and static modes. Regardless of the technology, by making the compaction machine a measuring device and insuring compaction requirements are met the first time, the compaction process can be better controlled to improve quality, reduce rework, maximize productivity, and minimize costs (White et al. 2006). Recent advancements with global positioning systems (GPS) present a significant benefit of real time spatial viewing of the roller measurement values. Some of these technologies have recently been implemented on full-scale earthwork construction projects in the United States (White et al., 2008), and its use is anticipated to increase in the upcoming years. In the U.S., effective implementation of this technology is following a path for which on-site calibrations and development of relationships between roller measurement values and traditional in-situ spot test compaction measurements (e.g. plate load test modulus, density, etc.) are required. This builds confidence in the technology and provides insight as to the key parameters affecting the machine measurement values. This paper describes two technologies – Compaction Meter Value (CMV) and Machine Drive Power (MDP) – and presents comparisons between the machine measurement values and various in-situ spot test measurements. A summary of empirical correlations are discussed. Some of the field measurements were evaluated using spatial modelling (variogram) and visualization techniques for a staged field test. Variogram analysis provides a unique opportunity to quantify and characterize the non-uniformity and spatial continuity of the measurements. The results should be of interest to both the earthwork industry and the pavement design community because of the ability to spatially document and quantify ground conditions. At the end of the paper, a brief summary of existing roller-integrated compaction monitoring specifications are presented for comparison, and some practical points for successful implementation of the technology are discussed.

2 Compaction Monitoring Technologies

The machines evaluated in this study were manufactured by *Caterpillar* and use a compaction measurement device supplied by *Geodynamik* that outputs the compaction meter value (CMV), resonant meter value (RMV), drum vibratory frequency (*f*) in Hz, and drum vibration amplitude (*a*) in mm. The CMV technology uses accelerometers installed on the drum of a vibratory roller to measure drum accelerations in response to soil behavior during compaction operations. The ratio between the amplitude of the first harmonic and the amplitude of the fundamental frequency is found to provide a good indication of the soil compaction level (see Thurner and Sandström, 1980). An increase in CMV indicates increasing compaction level. CMV is calculated as:

$$CMV = C \cdot \frac{A_1}{A_0} \tag{1}$$

where C = constant (300), A_1 = acceleration of the first harmonic component of the vibration, and A_0 = acceleration of the fundamental component of the vibration (Sandström and Pettersson, 2004). CMV is a dimensionless parameter that depends on roller dimensions (e.g. drum diameter, weight) and roller operation parameters (e.g. frequency, amplitude, speed). Reportedly, CMV at a given point indicates an average value over an area whose width equals the width of the drum and length equal to the distance the roller travels in 0.5 seconds (Geodynamik ALFA-030). RMV is not discussed here (see White et al., 2008 for details), but provides an indication of drum double jump.

Recent field studies by White et al. (2006) and (2007a) verified that roller-integrated machine drive power (MDP) may reliably indicate soil compaction for granular and cohesive soils. This is a relatively new concept and has not yet been incorporated into production machines. The use of MDP as a measure of soil compaction is a concept originated from study of vehicle-terrain interaction (Bekker, 1969). The basic premise of determining soil compaction from changes in equipment response is that the efficiency of mechanical motion pertains not only to the mechanical system but also to the physical properties of the material being compacted. MDP is calculated as:

$$MDP = P_g - WV\left(\sin\alpha + \frac{a}{g}\right) - (mV + b) \tag{2}$$

where P_g = gross power needed to move the machine (kJ/s), W = roller weight (kN), a = machine acceleration (m/s^2), g = acceleration of gravity (m/s^2), α = slope angle (roller pitch from a sensor), V = roller velocity (m/s), and m (kJ/m) and b (kJ/s) = machine internal loss coefficients specific to a particular machine (White et al., 2005). The second and third terms of Eq. (2) account for the machine power associated with sloping grade and internal machine loss, respectively. MDP is a relative value referencing the material properties of the calibration surface, which is generally a hard compacted surface (MDP = 0 kJ/s). Positive MDP values therefore indicate material that is less compact than the calibration surface, while negative MDP values would indicate material that is more compacted than the calibration surface (i.e. less roller drum sinkage).

Figure 1. Compaction monitoring technology with display system (upper left), GPS measurement using hand-held rover to link machine measurements with in-situ test locations for correlation analysis (upper right), and mobile geotechnical laboratory for rapid field testing and wireless data transfer (bottom).

Effective use of the compaction monitoring technology is aided in large part by the integration of a GPS system and an on-board compaction monitor which displays the roller location, machine measurement values (CMV/MDP), vibration amplitude and frequency, and roller speed. The technology enables a roller operator to make judgments regarding the condition of the compacted fill material in real-time. The Caterpillar rollers used in these studies had on-board display systems with integrated data acquisition systems and displayed real-time position and measurement values. The system uses real-time kinematics (RTK) GPS with accuracies of about

±10 mm in the horizontal plane and ±20mm in the vertical plane. On the roller, the GPS system is positioned over the center of the roller drum (Figure 1).

While these technologies offer significant advantages in earthwork construction practice, it also produces large data files that create analysis, visualization, transfer and archival challenges. ArcGIS modules can be utilized to perform traditional statistical analysis (comparisons to in-situ compaction test measurements), complex geostatistical analysis (evaluating proof areas for uniformity), data visualization, and data archiving (see White et al., 2007b and White et al., 2008). The data files that are generated from these rollers should ideally be transferred in real-time for data analysis and final decision making. This is quite possible with the recent advancements in wireless technology. The Iowa State University mobile geotechnical laboratory (Figure 1) for example can receive the machine signal in real-time and display the data prior to being sent through a satellite dish to a remote office location for additional analysis and archiving.

3 Field Evaluation of CMV/MDP

Results from extensive field testing and correlation analysis between CMV/MDP measurement values and in-situ spot test compaction measurements were documented recently by White et al. (2006), White et al. (2007a), White and Thompson (2008), and Thompson and White (2008). Experimental testing for these field studies involved construction of two dimensional test strips of about 30 m x 3 m, each comprising a different material type. The test strips with granular and cohesive soils were compacted using a CS-533 vibratory smooth drum roller and a CP-533 vibratory padfoot roller, respectively.

In-situ compaction testing devices included: (a) nuclear moisture density gauge to determine moisture and dry unit weight, (b) Keros and Zorn light weight deflectometers (LWD) to determine elastic modulus (E_{LWD}) (c) Clegg impact testers to determine CIV using 20-kg and 4.5-kg drop hammers, (d) dynamic cone penetrometer to determine penetration index (DCP Index), and (e) Static plate load test to determine elastic modulus (E_{PLT}). These test measurements (except static plate load test) were taken at ten locations while static plate load tests were performed at only one test location across the test strips. Test measurements were typically made after 1, 2, 4, 8, and 12 roller passes. The spot test measurement location information was obtained using GPS rover receiving a correction signal from a base station to pair the data with CMV/MDP measurement values.

3.1 Correlations between CMV/MDP and soil properties

Simple linear and multiple linear regression relationships to predict in-situ spot test compaction measurements (e.g. γ_d, DPI, E_{LWD}, E_{PLT}, CIV) using roller measurement values (CMV/MDP) for various soil types are discussed in detail in Thompson and White (2008), White and Thompson (2008), White et al. (2006) and (2007). A summary of these relationships for three granular and cohesive soil types is provided in Table 1. Unified Soil Classification System (USCS) group symbols for these soils are provided in Table 1. Note that the relationships (except for static plate load tests) presented in Table 1 are based on an average of ten in-situ compaction and CMV/MDP measurement values following a roller pass. Relationships to E_{PLT} are based on one test point following a roller pass.

For granular soils, logarithmic relationships were observed between in-situ soil compaction measurements and MDP, while linear relationships were observed for CMV. For the cohesive soils, regression relationships were improved in many cases for predicting soil compaction parameters (γ_d, DCP Index, etc.) from MDP when soil moisture content and MDP-moisture interaction parameters were included in the prediction models (Thompson and White, 2008). The R^2 values observed for the correlations generally exceeded 0.90, while R^2 values of less than 0.90 are mostly observed in estimating soil modulus. This is attributed to the complexity involved in estimating soil modulus and the relative variability associated with this measurement (White and Thompson, 2008).

4 Spatial Analysis of In-Situ and Roller Compaction Measurement Values

Roller-integrated compaction monitoring technology offers a unique advantage of quantifying and characterizing “non-uniformity” of compaction measurement values. This topic presumably should be of considerable interest to pavement engineers. White et al. (2007b) demonstrated the use of variogram analysis in combination with conventional statistical analysis to effectively address the issue of non-uniformity in quality assurance during earthwork construction. A variogram is a plot of the average squared differences between data values as a function of separation or lag distance, and is a common tool used in geostatistical studies to describe spatial variation. Three important features of a variogram include: sill, range, and nugget. *Sill* is defined as the plateau that the variogram reaches, *Range* is defined as the distance at which the variogram reaches the sill, and *Nugget* is defined as the vertical height of the discontinuity at the origin which mostly represents sampling error or short scale variations (Srivastava, 1996). From a variogram model, a low “sill” and longer “range of influence” can represent best conditions for uniformity, while the opposite represents an increasingly non-uniform condition.