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Assessing soil compaction using continuous compaction control and location-specific in situ tests

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ABSTRACT

Modern compaction equipment can be outfitted with sensors that allow for real-time monitoring of the compaction process, an approach that is commonly referred to as continuous compaction control (CCC). This paper describes the results from an experimental research study that was conducted to assess the effectiveness of CCC technology for construction of a roadway embankment using a sand containing a significant percentage of silty fines. During embankment construction, simultaneous machine drive power (MDP) and compactometer value (CMV) measurements were recorded, along with the corresponding position of the roller. Location-specific in situ "spot tests" were also performed to independently assess soil compaction, including nuclear density gauge (NDG) tests, soil stiffness gauge (SSG) tests, light weight deflectometer (LWD) tests, and dynamic cone penetrometer (DCP) tests. A comparison of the CCC measurements with the location-specific in situ test results was performed using spatial data analysis tools and statistical regression. The measured data, spatial and regression analysis approaches, and associated discussion that are presented provide valuable information for researchers and practitioners that are considering the use of CCC technology.

1. Introduction

Modern compaction equipment is now available with sensors that can monitor the compaction process of soil in real time [1]. Compaction measurement indices that are calculated from sensor-recorded data are typically coupled with roller position measurements that are made with onboard real time kinematic global positioning system (RTK-GPS) equipment [2]. Taken together, this information allows for construction of spatial maps that provide feedback to both the equipment operator and field personnel who are responsible for quality assurance or quality control (QA/QC) of the compaction process [1]. This instrumentation-enhanced assessment of soil properties during the compaction process is commonly referred to as *continuous compaction control* (CCC). Further compaction equipment improvements allow for *intelligent compaction* (IC), a mechanism whereby CCC data is used to adjust the operation of the compactor in real time to optimize the compaction process and achieve more uniform soil compaction [3–4].

For granular soils, vibration-based measurement indices are typically utilized in CCC, such as the compactometer value [5–6], or others that attempt to more directly assess soil stiffness or modulus [4,7]. For fine-grained soils, which typically do not compact well using vibratory compaction, static rollers that utilize measurement indices based upon machine drive power measurements are typically employed [8]. Some studies have successfully used both vibration-based measurements and machine drive power measurements concurrently [9–10].

Since the introduction of CCC technology, a number of studies have been performed to relate roller measured values to various location-specific measurements of density or modulus (or other performance indicators such as penetration resistance or California bearing ratio) made using a variety of in situ test devices [1,7,9,11–24]. A significant number of the earlier publications on this list are in German, and/or are in reports or dissertations that can be somewhat difficult to obtain. Many of the peer-reviewed conference or journal publications that do exist to date are the product of data sets that were collected during a 3.5-yr National Cooperative Highway Research Program (NCHRP) project conducted by researchers from Colorado School of Mines and Iowa State University in the U.S.A., who worked in conjunction with a number of state-level Departments of Transportation (DOTs) [1]. Although the data that has been collected in this area to date has been excellent, the authors feel that additional data is beneficial for other

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researchers, the practicing community, and various government agencies to make their own assessments of emerging CCC and IC technologies.

In this paper, the authors present a new CCC data set that compares roller measured values with location-specific in situ test results. This data was collected during compaction of a test embankment that was constructed using a sand containing a significant percentage of silty fines, as part of a research project funded by the Delaware Department of Transportation (DelDOT), in the U.S.A. The CCC indicator values that were recorded during this study include concurrent machine drive power (MDP) and compactometer value (CMV) measurements. The in situ "spot" tests that were performed between compactor passes include nuclear density gauge (NDG) tests, soil stiffness gauge (SSG) tests, light weight deflectometer (LWD) tests, and dynamic cone penetrometer (DCP) tests. The measured data, spatial and regression analysis approaches, and associated discussion that are presented may be useful for researchers and practitioners that are considering the use of CCC technology.

2. Embankment construction

For this project, a 61-m long × 6-m wide (200 ft × 20 ft) embankment was constructed using "select fill" granular material [25]. The embankment was constructed to an approximate total final height of 0.9 m (3.0 ft), by compacting five layers with a target loose lift thickness of 20.3 cm (8 in), following Delaware general specifications for road sub-base construction [25]. Actual lift thicknesses at the end of the compaction process varied slightly throughout the compacted area, as discussed in Meehan et al. [26] and Cacciola et al. [27]. Specific details about the soil placement and moisture conditioning process that was utilized are available in Tehrani [28], Meehan and Tehrani [10], and Meehan et al. [29].

After soil placement and moisture conditioning, each soil lift was compacted using a Caterpillar CS56 vibratory smooth drum roller, which simultaneously measured both MDP and CMV values. An onboard RTK-GPS system was used to accurately determine the location of the compactor as each roller measurement was recorded. The roller drum was 2.1 m (7 ft) wide with an operating mass of 11,414 kg (25,164 lbs). Compaction was performed using low and high amplitude vibration (0.85 and 1.87 mm, 0.033 and 0.074 in) at a vibratory frequency of 31.9 Hz. The roller speed was kept relatively constant during compaction, at about 3.25 km/h (2.02 mph). To speed up the compaction process, high amplitude compaction was performed on the loose materials in the first pass for each layer, and the following passes were performed using low amplitude compaction [10].

Each lift was compacted in a series of passes using three side-by-side lanes with approximately 15 cm (6 in) of overlap at the edges of each compacted soil "lane". For lifts 1 through 5, a total of 6 to 9 compactor passes were performed to achieve the required level of compaction. The actual number of passes utilized was determined by the compactor operator in the field based upon CCC values observed in real-time in the roller cab and technician experience from compaction of this borrow soil at other field construction projects [10,29].

3. In situ testing using spot testing tools

At the end of compaction for each lift, and for Lift 5 after each pass of the compactor, a series of in situ tests were performed at consistent intervals throughout the test area to monitor the process of soil compaction. The tests that were conducted include NDG tests, SSG tests, LWD tests, and DCP tests. Each of these tests was conducted in general accordance with standard practice in the United States [30–34]; for brevity, the step-by-step details of each test procedure are omitted here.

The SSG that was used in this study was manufactured by Humboldt Mfg. Co; this device is also commonly referred to by its industry trade name, the *GeoGauge*. Two LWDs were used in this study (both manufactured by Zorn-Instruments), the first with a plate diameter of 300 mm (LWD 300), a falling mass of 10 kg, and a drop height of 730 mm, and the second with a plate diameter of 200 mm (LWD 200), a falling mass of 10 kg, and a drop height of 540 mm. The DCP that was used in this study (manufactured by Kessler Soils Engineering Products, Inc.) had a falling mass of 8 kg, a drop height of 575 mm, an overall penetration depth of 152 mm, and a conical point sloped at 60°. The basic operating principles behind each of these in situ tests are described in more detail in Tehrani [28]; further details about the in situ testing program that was utilized are available in Meehan et al. [29].

For the SSG tests, modulus values were calculated using the method described by Humboldt Mfg. Co. [35]. For both the LWD 300 and LWD 200 tests, modulus values were calculated from the soil's surface deflection under the LWD plate using Boussinesq's equation [36]. For the DCP tests, both "average" (DCP-A) and "weighted mean" (DCP-M) cone penetration indices were calculated using the methods described by White et al. [19].

Each test series was accompanied by disturbed soil sampling, for later determination of the moisture content [37], particle size characteristics [38–39], and 1 pt-proctor compaction characteristics [40]. The order of the in situ tests and sampling that were performed was selected to minimize the effect of soil disturbance on the in situ test results. At each test location, the aforementioned in situ tests and sampling were performed in the following order: LWD 300, LWD 200, SSG, NDG, DCP, and finally bulk soil sampling. From lift to lift (or pass to pass on Lift 5), a slight test location offset was made with respect to previous test locations, to minimize the influence of prior soil sampling on the in situ test results for the soil layer that was being tested.

A detailed discussion of the measured in situ test values, their statistical variation, and how they compare with each other is available in Meehan et al. [29] and Tehrani et al. [41]. In situ test results of interest for the current study are provided in Table A1. Average in situ test results for each lift and pass are provided in Table A2.

4. Soil properties

Grain size analysis results for field samples taken at the in situ test locations are shown in Fig. 1. Atterberg limit tests [42] conducted on the soils indicated that the finer portion of the soils examined in this study were nonplastic in nature [28]. From this data, the "select fill" materials that were used for embankment construction classify as either a poorly graded sand with silt (SP-SM) or a silty sand (SM) [43]. The former classification was predominant, as indicated by 36 out of the 53 soil classification tests that were performed; however, in general, the material was relatively uniform for field construction of this type (mean grain size and coefficient of variation of the No. 4, 40, and 200 sieve sizes is: $\mu_4 = 90.0\%$, $c_{v,4} = 0.04$, $\mu_{40} = 35.4\%$, $c_{v,40} = 0.08$, $\mu_{200} = 11.7\%$, $c_{v,200} = 0.14$), and only had two classifications because it tended to fall at the boundary between two soil types in the Unified Soil Classification System (USCS).

5. CCC measurement indices

The Caterpillar CS56 vibratory smooth drum roller that was used in this study made simultaneous measurements of MDP and CMV. MDP values can be calculated using the following equation [44]:

$$MDP = P_n = P_g - WV\left(\sin\alpha + \frac{a}{g}\right) - (mV + b) \quad (1)$$

where P_n = net power required to propel the compactor through an uncompacted layer of fill; P_g = gross power needed to move the machine; W = roller weight; V = roller velocity; a = acceleration of the machine; g = acceleration of gravity; α = slope angle; and m and b are machine internal loss coefficients specific to a particular machine.

The compactor that was used in this study recorded roller-specific machine drive power values, which are commonly referred to as