Justification of chosen values of the weight coefficients of the compaction value for continuous compaction control systems for vibration rollers

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Abstract. The problem of monitoring the compaction of road construction materials in structural construction is currently relevant. The methods of quality control of compaction of road construction materials currently used in Russia during quality inspection do not provide a way to estimate more than 0.1% of the total compaction area. Today there is a wide variety of continuous compaction monitoring systems for vibratory rollers. Such systems allow operators of vibratory rollers to monitor the condition of compacted material in real time, which significantly improves the quality of road construction. The operation of most monitoring systems is based on the compaction index obtained from the analysis of the acceleration spectrum of the vibratory drum. When a new soil compaction monitoring system is only starting to be developed, it is necessary to develop and test in the field a new, more perfect compaction indicator, and to compare it with the existing compaction values. A field research has provided us with signals from vibration acceleration sensors placed on the frame of a vibratory drum and acceleration spectra of the vibratory drum using ZETLAB software made by ETMS. To calculate the proposed indicator, the received data was processed in STATISTICA v.10. The final correlation analysis was performed using the CORREL function found in MS Excel 365 and its financial and scientific data analysis tool. As a result of this correlation analysis, it was found that the proposed Compaction Value has the highest coefficient of linear correlation with the value of the dynamic deformation module $E_{vd}$ in all areas of the field research. In this regard, it can be concluded that using the proposed Compaction Value is reasonable in the development of a new continuous monitoring system for compaction of road-building materials with vibratory rollers.

1. Introduction
Despite the large number of modern technologies implemented, the problem of compaction control of road-building materials (hereinafter, RBM) in the construction of engineering structures on subsoil bases still remains relevant, and it's one of the most important problems in some areas of construction. Methods of quality control of RBM compaction currently used in Russia for acceptance of works (in accordance with SP 34.13330.2012 "Automobile roads. Updated living edition of SNiP 2.05.02-85*" and PNST 311-2018 "General automobile roads. Deformability indicators of structural layers of pavement from incoherent materials and subgrade soil. Technical requirements and determination methods") allow an evaluation of no more than 0.1% of the total compacted area. Domestic and foreign researchers provide various recommendations on a choice of model of vibratory rollers and justify their operation modes for compaction of various RBM in specific technological conditions [1].
[2], as well as the advanced methods of the express control of RBM compaction [3], [4]. However, even taking into account the recommendations for operation and optimal choice of equipment, it is necessary to monitor the process of RBM compaction by a vibratory roller across the operation area to avoid the risk of undercompaction of RBM, which leads to premature destruction of roads.

Today there is a wide variety of continuous RBM compaction control systems (hereinafter, CRBMCCS) for vibratory rollers. Such systems allow operators of vibratory rollers to monitor the condition of compacted RBM in real time, which significantly improves the quality of road construction and provides a way to document the results of compaction. CRBMCCS production leaders are the USA, Japan, Germany, and Sweden, since the same countries serve as the bases for the world-renowned manufacturers of vibratory rollers and other construction equipment — HAMM, Dynapak, Caterpillar, Sakai, as well as a well-known Scandinavian company "Trimble" specializing on developing of the geodetic and navigating equipment. Today, Russia lags far behind even in the use of existing CRBMCCS of foreign manufacturers, not to mention their local counterparts. The problem of using the existing foreign CRBMCCS on vibratory rollers made in Russia consists both in essential difference of technical characteristics of locally manufactured vibratory rollers from foreign counterparts, and in it being necessary to coordinate the data received from a CRBMCCS with local regulations, which regulate the indicators of RBM compaction quality during a quality inspection. All the above-mentioned problems prove that the local system of continuous control of compaction of road-building materials by vibratory rollers should be designed.

2. Problem statement

Each CRBMCCS provides the operator of a vibratory roller with a numerical value of a compaction index determined in real time, calculated according to an individual algorithm [5]. In order to create a local CRBMCCS, it is necessary to design a compaction value that would correlate well with the value of the dynamic deformation module Evd, which is used to assess the compaction of soils and stone materials in many countries, and from 2018 is included in the preliminary national standard PNST 311-2018. This should demonstrate the performance of this compaction value and advance the development of the new CRBMCCS.

CRBMCCSs are installed on vibratory rollers of the world's leading manufacturers (Dynapak, HAMM, Caterpillar, Sakai). The functionality of these systems is based on determining the compaction value, which is individual for each control system. The functionality of most CRBMCCSs is based on the calculation of the compaction value obtained by analysing the acceleration spectrum of a vibratory drum (Figure 1). [6], [7], [8].

The hardware of most CRBMCCS consists of an accelerometer, which is installed on a vibratory roller and measures the vertical acceleration of a vibratory drum during the compaction of RBM.
Accelerometer readings are processed in real time in the control unit (it charts an acceleration spectrum, after which a compaction value is calculated). After processing the signal, the calculated compaction value is transmitted to an output device on the roller's instrument panel. After that, the roller operator decides if they need to continue their work, change the compaction mode, or finish the work. Below are the formulas for determining the compaction values currently used by the world's leading manufacturers of vibratory construction equipment in their CRBMCSSs.

Compaction Meter Value (hereinafter, CMV) [11], [12], [13]:

\[
CMV = C \cdot \frac{A_{2f}}{A_f},
\]

where: \(A_f\) – the amplitude of a harmonic of the vertical acceleration spectrum of a vibratory drum on the frequency of changes in the driving force \(f\) (nominal frequency of vibrations of the drum in the vibratory roller), m/s²; \(A_{2f}\) - the amplitude of the harmonic of the vertical acceleration spectrum of the vibratory drum at the frequency \(2f\) (second harmonic amplitude of the vertical acceleration spectrum of the vibratory drum), m/s²; \(C\) – calibration rate (usually 300) [14].

Resonance Meter Value (hereinafter, RMV), also called Bouncing Value [11], [15]:

\[
RMV = BV = C \cdot \frac{A_{0.5f}}{A_f},
\]

where: \(A_{0.5f}\) – the amplitude of a subharmonic of the vertical acceleration spectrum of the vibratory drum in the vibratory roller at the frequency \(0.5f\), m/s².

Compaction Control Value (hereinafter, CCV) [10], [11], [12]:

\[
CCV = \left(\frac{A_{0.5f} + A_{1.5f} + A_{2.5f} + A_{3f}}{A_{0.5f} + A_{2f}}\right) \cdot 100%,
\]

where: \(A_{1.5f}\) – the amplitude of a subharmonic of the vertical acceleration spectrum of the vibratory drum at the frequency \(1.5f\), m/s²; \(A_{2.5f}\) - the amplitude of a subharmonic of the vertical acceleration spectrum of the vibratory drum at the frequency \(2.5f\), m/s²; \(A_{3f}\) - the amplitude of a subharmonic of the vertical acceleration spectrum of the vibratory drum at the frequency \(3f\), m/s².

The authors propose a Compaction Value (hereinafter, CV) for new CRBMCSSs [16]:

\[
CV = \left(\frac{K_{0.5f}A_{0.5f} + K_{1.5f}A_{1.5f} + K_{2.5f}A_{2.5f} + K_{3f}A_{3f}}{K_{0.5f}A_{0.5f} + K_{2f}A_{2f}}\right) \cdot K,
\]

where: \(K\) – the total calibration constant; \(K_{0.5f}, K_{1.5f}, K_{2f}, K_{2.5f}, K_{3f}\) – the significance ratios of the amplitudes of harmonics of the vertical acceleration spectrum of the vibratory drum at frequencies: \(0.5f, 1.5f, 2f, 2.5f\) and \(3f\) respectively.

To calculate the numerical value of the proposed CV, it is necessary to determine the numerical values of weight coefficients \(K_{0.5f} \ldots K_{3f}\) after considering the technical characteristics of the vibratory roller used and the type of compacted RBM. For this purpose, the amplitude values of harmonics and subharmonics \(A_{0.5f} \ldots A_{3f}\) were determined in the vibration acceleration spectrum of the vibratory drum, and the STATISTIKA software was used to determine the numerical values of weight coefficients \(K_{0.5f} \ldots K_{3f}\), providing the best correlation with the values of the dynamic deformation modulus \(E_{vd}\) of the studied RBM when compacting with a given vibratory roller. The results of mathematical modeling [17] showed that the CV is the most sensitive to changes in the characteristics of RBM, in comparison to CMV and CCV. However, experimental research is needed to ensure the validity of the modeling results obtained.

3. Theory
Experimental studies were conducted on the DM-617 vibratory roller (manufactured by Zavod Dorozhnyh mashin, Rybinsk) with the following characteristics: operating mass of the vibratory roller \( m = 16000 \text{ kg} \); weight distribution in axes (front axle/rear axle) - 55\% / 45\%; driving force \( P = 230 \text{ kN} \); roller vibration frequency \( f = 30 \text{ Hz} \).

Vibration acceleration sensors were installed on the above-mentioned vibratory roller to register the vertical component of the vibration acceleration of the vibratory roller [18]. Compacted material - crushed stone, grade 800, fractions 40...70 and 20...40 mm. Two areas have been chosen to be used to conduct experimental research at the site. The areas were strips of crushed stone deposited on a compacted sand layer 0.3...0.35 m thick, 12 m long, and 3 m wide. Each area was in turn divided into three sections of equal length. After each pass of the roller, the dynamic deformation modulus \( E_{vd} \) of the layer was measured using the ZORN ZFG 3.0 dynamic loading unit in each section of the area. Also, as the vibratory roller passed over each section of the area, readings of the acceleration sensor on the drum were recorded at each pass, which were later used to obtain the acceleration spectrum of the drum and to determine CMV, CCV, and CV.

4. Experiment results
The results of calculations of various parameters of RBM compaction by DM-617 vibratory roller at areas No. 1 and No. 2, depending on the values of the dynamic deformation modulus \( E_{vd} \) at different sections within each area are shown in the figures below (Figure 2 – Figure 7).

![Figure 2. The changes in CMV depending on \( E_{vd} \) on various sections of the plot No. 1.](image-url)

![Figure 3. The changes in CCV depending on \( E_{vd} \) on various sections of the plot No. 1.](image-url)
Figure 4. The changes in CV depending on $E_{vd}$ on various sections of the plot No. 1

Figure 5. The changes in CMV depending on $E_{vd}$ on various sections of the plot No. 2

Figure 6. The changes in CCV depending on $E_{vd}$ on various sections of the plot No. 2
After analysing the charts, we see that each value demonstrates well enough the accumulation of the density of RBM with each pass. However, it is necessary to numerically determine which of the compaction values shows the density accumulation more accurately. Therefore, a correlation analysis of the obtained charts was performed using the CORREL function found in MS Excel 365 and its financial and scientific data analysis tool. We have established the dependence between the dynamic deformation modulus $E_{vd}$ and the calculated CMV, CCV, CV. The analysis provided us with a statistical quantitative measure of value estimation — a linear correlation coefficient. The obtained values of the linear correlation coefficient are presented in the following table (Table 1).

**Table 1.** Line coefficients of CMV, CCV and CV correlations with dynamic deformation modulus $E_{vd}$ of a layer of crushed stone (for all no. 1 and no. 2 areas).

| $E_{vd}$ (Plot No. 1; Sections 1, 2, 3) | CMV | CCV | CV  |
|----------------------------------------|-----|-----|-----|
|                                        | 0.726 | 0.784 | 0.767 |
| $E_{vd}$ (Plot No. 2; Sections 1, 2, 3) | 0.561 | 0.620 | 0.644 |
| $E_{vd}$ (Plot No. 1 and No. 2; Sections 1, 2, 3) | 0.532 | 0.581 | 0.622 |

5. **Conclusions**

The results of the presented experimental studies show that the offered Compaction Value, if used in CRBMCCSs at reasonable weight coefficients $K_{0.5f} \ldots K_{3f}$, provides the best correlation with the dynamic deformation modulus $E_{vd}$ of the RBM in question, in comparison with CMV and CCV used nowadays. However, all three studied indicators are characterized by a rather significant variation of values, which means that they cannot be recommended to be used at the quality inspection. At the same time, these indicators can be used for express control.

An important requirement to the indicators used in the CRBMCCS inside the vibratory rollers is the ability to determine the transition of the vibratory roller in unwanted and dangerous vibration modes "double jump" and "swinging" [19]. To study the identification of different vibration modes, including undesirable and dangerous ones, using the proposed CV indicator requires additional research.

It is also necessary to expand the list of vibratory roller models and types of RBM to form sets of weight coefficients $K_{0.5f} \ldots K_{3f}$, used to calculate the CVs when compacting different DSM, which also requires further experimental studies.
At the same time, the very possibility of applying the CV in the CRBMCCS in vibratory rollers has been experimentally confirmed.

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