A State-of-the-art Review of Compaction Control Tests Methods

PhD. Student Eng. **Andrei BURAGA[1,*]**, Prof. Dr. Eng. **Carmen Nicoleta DEBELEAC[1]**

[1]"Dunarea de Jos" University of Galati, Engineering and Agronomy Faculty in Braila, Braila, Romania

* andrei.buraga@dmmc.utm.md; carmen.debeleac@ugal.ro

Abstract: *Quality control methods have been used by construction civile industry and road for many years to control the compaction process carried out, either of the soil or of the asphalt mixtures. These control procedures are based upon experimental and/or statistical concepts and their goal are to be an instrument to assist the contractor to carry out the execution checks in insuring that impose degree compaction was achieved in accordance with technical project of the works. These concepts are built around the idea according to which it is possible to randomly select a small sample of a soil or asphalt mixture and then to predict from this sample an average value of compaction quality to be assigned to the entire area of the layer tested. For the most part, these aspects are valid in our country, but the technical regulations of developed countries provide for a variety of methods based on the in-situ measurement of specific compaction parameters in order to predict the quality of the area under control. The paper will describe the methods used in Romania (laboratory and in-situ tests) along with those implemented in the world and used with remarkable results.*

Keywords: *Compaction, soil, laboratory and in-situ tests, control, quality*

1. Introduction

Soil compaction testing is the process by which the density property of a material (which can be soil or mixture asphalt) soil mass is increased in the field using the various technologies, and monitored by quality control delegates from the local building department. Thus, during the compaction of backfill material, density testing is impetuously necessary in order to evaluate whether the final terrain compaction levels are adequate to support building foundations, roads, bridges, etc. These checks are made using test methods in the laboratory or directly on the field and will be briefly presented in the paper as classic methods used here in Romania, along with modern methods successfully applied in countries with highly developed industries.

2. Quality control of soils compaction in Romania

As known, soil compaction is defined as the increase of bulk density or decrease in porosity of soil due to externally or internally applied loads. Taking this aspect into account, at the compaction works of the soils it is necessary to know some characteristic parameters that are determined by different methods (static or dynamic), both in the laboratory, and in-situ, described below:
a) laboratory tests: oedometric test (STAS 8942/3-90 [2]), cyclic triaxial test (NP 125:2010, Annex B [3]), Proctor test (STAS 9850-89 [4]). On the basis of these laboratory geotechnical tests, the followings are determined: the time for complete compaction of the terrain (NE-008-97 point 2.14.), oedometric modulus of deformation, drawing the stress-strain curve and the time variation of the pore pressure, optimum compaction moisture and maximum dry weight or maximum dry density, compaction degree, Proctor curve;
b) in-situ tests: evaluation of the static modulus of linear deformation of soils (by calculation, based on the oedometric modulus according to STAS 3300/2-85 [5], point 3.4.5, or by direct measurement in-situ, by the plate loading test according to STAS 8942/3, evaluation of the settlement of soils under a single passing of the compactor (and by correlating with the values of the linear deformation modulus of the terrain, the experimental curves within figure 11 of NE-008-97 result), experimental evaluation of the layer thickness (according to NE-008-97 point 2.6 applying the procedure described in the NE-008-97, Annex 2.2., point 2).
Based on these results, the geotechnical parameters will be evaluated for adequate application of the technological solution, in order to obtain a higher compaction efficiency.

In addition, the main parameters evaluated in-situ tests, which enable the identification of the degree of field compaction, according with Romanian Regulations, are summarized in the Table 1.

Table 1: Romanian Regulations and methodologies for compaction quality control

Requirement	Application methodology	Romanian Regulations
Correlation of parameters associated with the vibratory roller-terrain system	Measuring the width of the contact area between the compactor roller and the ground and, then, by checking the values within the range for the ratio of measured width divided by roll diameter, depending on the degree of compaction resulting from the Proctor test	NE-008-97
Duration of soil compaction and the effective consolidation effort	Calculated on the basis of the specific settlement and the primary consolidation time obtained by the Casagrande semi-logarithmic representation method	NE-008-97 STAS 8942/1- 90
	In-situ, by measurements of pressure doses to determine the pressure transmitted in the layer	
Modulus of elasticity E_s, G_d and the damping ratio ζ of the terrain	Testing of loading with the plate equipment on the terrain to determine static modulus of linear deformation	NP125:2010 STAS 3300/1-85 Annex C, Table 9 NP 125:2010 - Annex D
	Cyclic triaxial testing for each loading cycle to determine dynamic deformation modulus	
	Hysteresis curve (axial stress-deformation, on each cycle) to determine the damping ratio	
	In-situ measurements to determine the logarithmic decrement of the vibrations due to the free fall of a weight	

Quality control and quality assurance (QA/QC) of the compaction process are indispensable for the long-term performance of roads or foundation works. The practical methods of on-site measurement, provided in our national standards, ensure the assessment and verification of compliance with the requirements of the technical project of the respective compaction work. However, these methods also have shortcomings and cannot provide complete information about the quality of compaction.

In the case of the topic addressed in this paper, in Romania there are intense concerns in the direction of the study and numerical simulation, on the one hand, of the functional behavior of vibratory compactors, and on the other hand, of the transmissibility and amplitude of vibrations felt in soils (filling, weakly cohesive, with consolidation, etc.) [6-13]. All these technological aspects have a great influence on the efficiency of the compaction process, facilitating the fulfillment of the proposed goal (by reaching the required compaction coefficient after a small number of passes, according to the regulations in the field of soil compaction).

With the technical progress in the field of automation and information processing, an intelligent technology has been implemented on the compaction machines, which has a great potential to solve some of the shortcomings of the classical standardized methods for evaluating the quality of the compaction process. Such intelligent systems for monitoring the parameters of the compaction process are made up of hardware and software components capable of providing information of this technological process in real time, but also their management through an efficient management system. A brief presentation of them, used more and more in developed countries, will be given below.

3. Best practice for quality control of soils compaction worldwide

The performance evaluation system of the vibration compaction process is carried out based on the scheme in Figure 1 based on the identification of some parameters that describe the behavior of the compacted material in terms of certain physical and mechanical properties. Certainly, two important compaction parameters namely the dry weight (γ_{kmax}) and optimum moisture content

(W_{opt}) values can be obtained by standard compaction test in laboratory. But, in order to estimate some other compaction parameters, many studies have been approaced by different researchers. These bring in attention that in-situ control of the compaction process requires the appropriate choice of the following parameters: compaction point spacing, vibration frequency, probe penetration and extraction, and duration of compaction. At the end of the compaction process, the soils fall into five types, from the point of view of their compaction efficiency, as follows: good, fine, ordinary, poor and bad. Each soil type corresponds to a wide range of specific parameters, such as those centralized in Table 2.

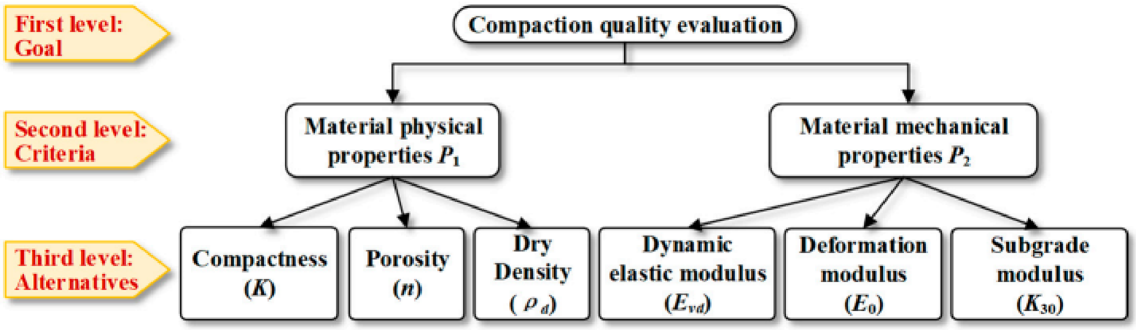

Fig. 1. Indicators for evaluating the quality of the compaction process

Table 2: The standard classification level for physical-mechanical indices in soil compaction

Quality level	I (good)	II (fine)	III (ordinary)	IV (poor)	V (bad)
D (%)	>99	98-99	95-98	90-95	<90
ρ_d (x10^3 kg/m^3)	>2.27	2.25-2.27	2.23-2.25	2.21-2.23	<2.21
E_{ud} (MPa)	>9.7	9.5-9.7	9.3-9.5	9.1-9.3	<9.1
E_0 (MPa)	>16.5	16-16.5	15.5-16	15-15.5	<15
k_{30} (MPa/m)	>29	27.5-29	26-27.5	24.5-26	<24.5
Dimensionless value	50	40	30	20	10

The parameters in Table 2 have the following significations: D is the degree of compaction; ρ_d – density of the material in the dry state; E_{vd} – the dynamic modulus of linear deformation; E_0 – static modulus of linear deformation; k_{30} - layer stiffness.

The test methods acceptable for use for quality assurance of pavement and subgrade materials that have the potential to reliably provide a direct measure of the strength or in-situ modulus value, and which offer significant time savings in turnaround time of test results, in Figure 2 are shown.

Fig. 2. Usual devices for in-situ measurements of the terrain properties with:
Light Weight Deflectometer, Dynamic Cone Penetrometer, Clegg Hammer, Plate Load Testing.

Nowadays, on an international level, various devices as multi-purpose units for acquiring, measuring and processing vibration signals are available, assimilated with mobile laboratories for in situ testing of the quality of the works performed (compaction, vibro-injection, etc.). Some such examples are illustrated in Figure 3.

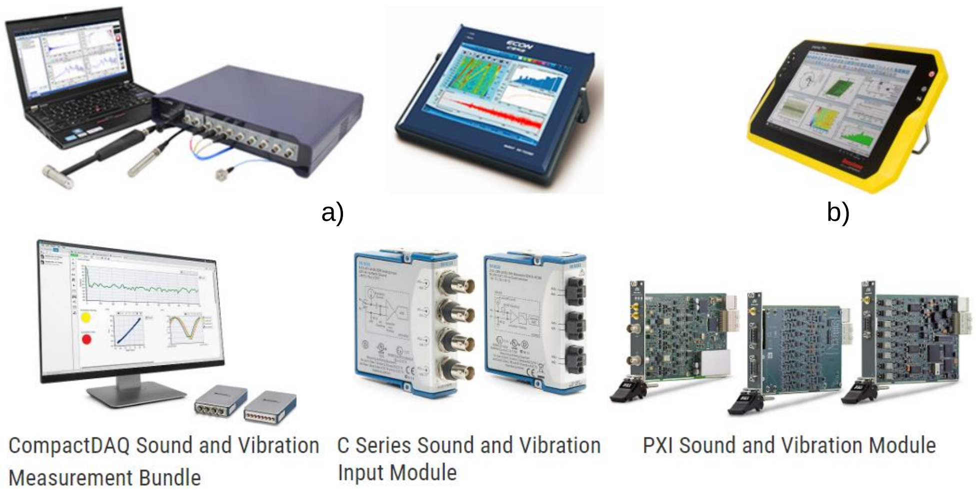

Fig. 3. High-performance systems for acquisition, measurement and processing of vibration signals:
a) Econ MI generatio 7 / Dynamic Signal Analyzer Module [14];
b) Impaq Pro Portable Vibration Analyzer [15];
c) PC-Based Sound and Vibration Devices / PXI Sound and Vibration Module USB 4431 [16].

More than 30 years ago, the European Community initiated the implementation of continuous compaction measurement and control (CCC) methods, so that today modern vibratory compactors are equipped with continuous (in situ) monitoring and control systems of influencing parameters major impact on the performance of the terrain vibration compaction process. Thus, three CCC systems are known worldwide, which will be briefly described below.
CCC – compactometer that monitors the variation of the ratio between the acceleration amplitudes according to the frequency, by evaluating the CMV or CCV parameters as:

$$\begin{cases} CMV = C_0 \cdot \dfrac{A_{2\omega}}{A_{\omega}} \\ CMV = \left(\dfrac{A_{0,5\omega} + A_{1,5\omega} + A_{2,5\omega} + A_{3\omega}}{A_{2,5\omega} + A_{3\omega}}\right) \cdot 100 \end{cases}, \quad (1)$$

where: A_{Ω} and $A_{2\Omega}$ are the amplitudes of the acceleration signal monitored on the vibratory roller (Figure 4) at the fundamental frequency Ω and of the first harmonic component of the real-time acceleration response signal; $A_{0.5\Omega}$ represents the first subharmonic and $A_{1.5\Omega}$, $A_{2.5\Omega}$ and $A_{3\Omega}$ represent the corresponding higher order harmonics. C_0 is a calibration constant that has values in the range 250 - 350.

Fig. 4. CMV technology [17]

The studies carried out by different researchers showed that by knowing the spectral composition of the acceleration signal of the vibratory roller in its vertical movement, the condition of the layer over which the vibratory roller moves can be identified. In the analysis of the acceleration signal, only the existence of the fundamental harmonic is noticeable, in the case of loose terrains, in contrast to the presence of a wide spectrum of higher harmonics, with increasingly smaller amplitudes until zero, in the case of terrains with very high rigidity, which have reached the maximum degree of compaction (Figure 5).

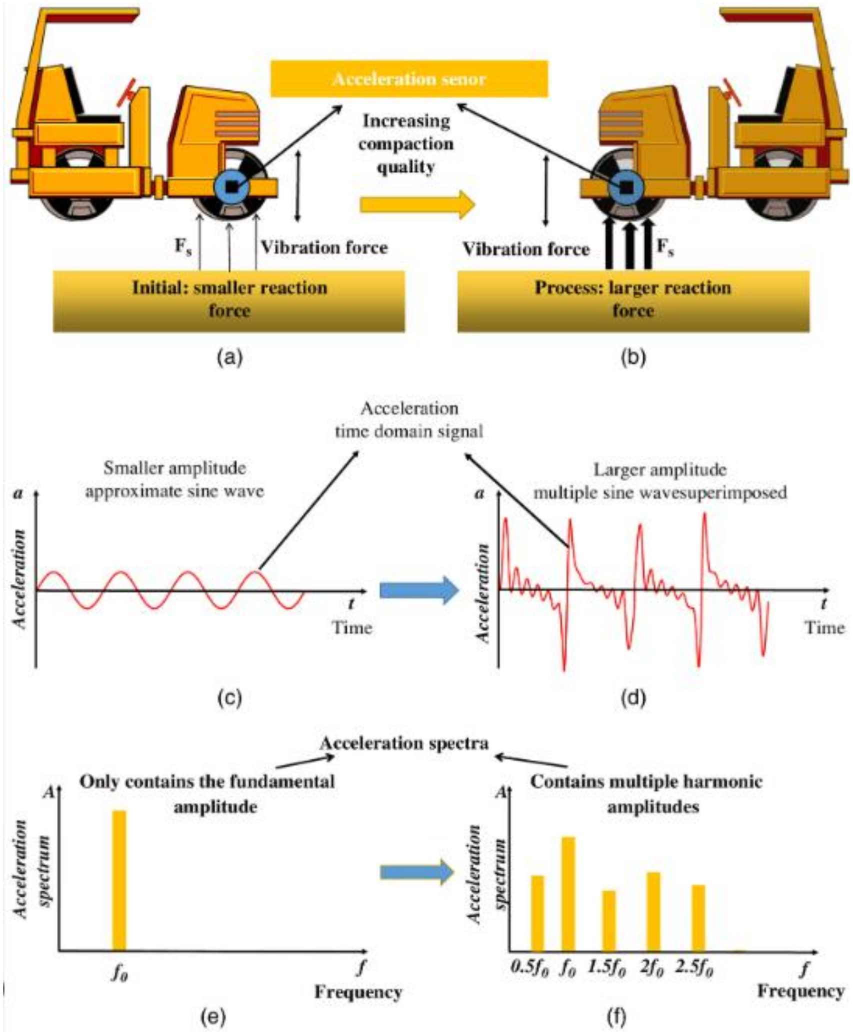

Fig. 5. The spectral composition of the vibration roller acceleration signal [18]

It is noted that the analysis of the response of the vibratory roller to the interaction with the ground provides important information (in situ) about the progress of the compaction process at any time, i.e. after each pass of the technological equipment over the layer. Taking into account the proportionality of the contact force between the roll and the ground, the law of variation of the measured acceleration signal provides information about the dynamic behavior of the roll upon impact with the ground. Through frequency spectral analysis of the contact force (with variation law determined on the basis of the measured acceleration) the nature of the vibrator roller-ground contact can be identified, which can be of three types: permanent, periodic and chaotic. Thus, Figure 6 shows how to know the state of compaction of the layer according to the spectrum of the harmonics of the monitored signal. In practice, however, during the technological process of compaction, the movement of the vibratory roller can be periodic or chaotic, which implies either a continuous contact between the vibratory roller and the ground, or periodic or chaotic loss of contact. In each individual work situation, the force of interaction between the vibratory roller and the ground has different dynamic behavior, being influenced by the stiffness of the material being compacted, as well as by the speed of the machine.

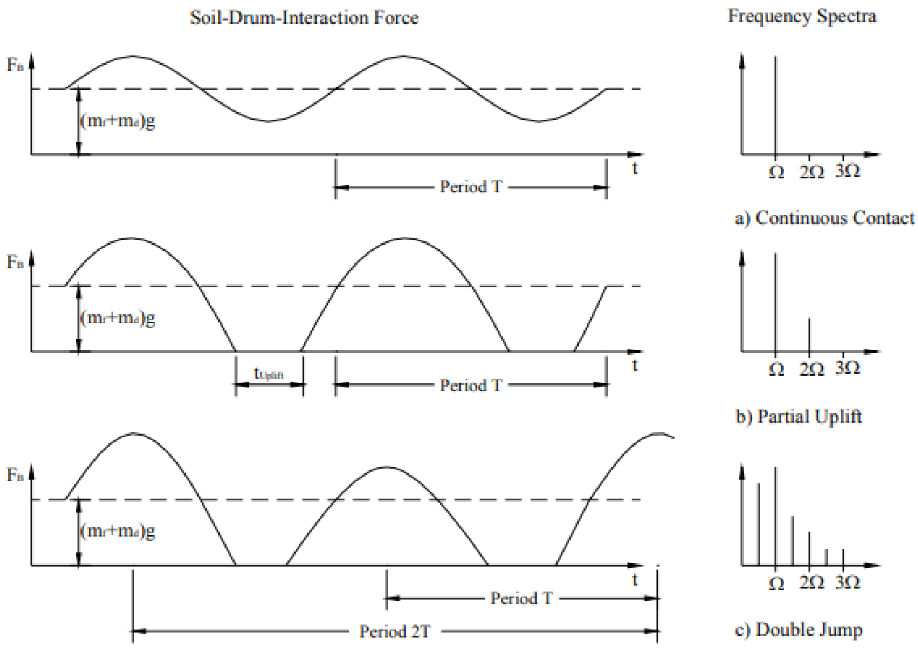

Fig. 6. Spectral analysis of the vertical acceleration of the vibratory roller – terrain in the 3 phases of contact [19]:
a) permanent contact; b) periodic contact; c) chaotic jump.

Based on the CMV parameter (which measures the stiffness of non-cohesive soils, with layer thickness between 1...1.2 m), in the specialized literature [20] there are references about the determination of others, which specifically contribute to the definition of the compaction states of the layers, such as: RMV (resonance meter value, see definition in eq. 2), OMV (oscillometer value) or CCV (continuous compaction value).

$$RMV = 100\,\frac{A_{0,5\omega}}{A_{\omega}} \tag{2}$$

CCC – terrameter is another system that is based on the monitoring of two compaction status indicators, as follows:

a) the variation of the energy transferred to the ground during the passes of the vibratory compactor, by evaluating the OMEGA parameter [Nm];

b) the variation of the dynamic modulus of elasticity of the land during the passage over the layers of the land, by monitoring the E_{vib} parameter [MN/m^2].

The working principle by which the E_{vib} parameter is evaluated is illustrated in Figure 7.

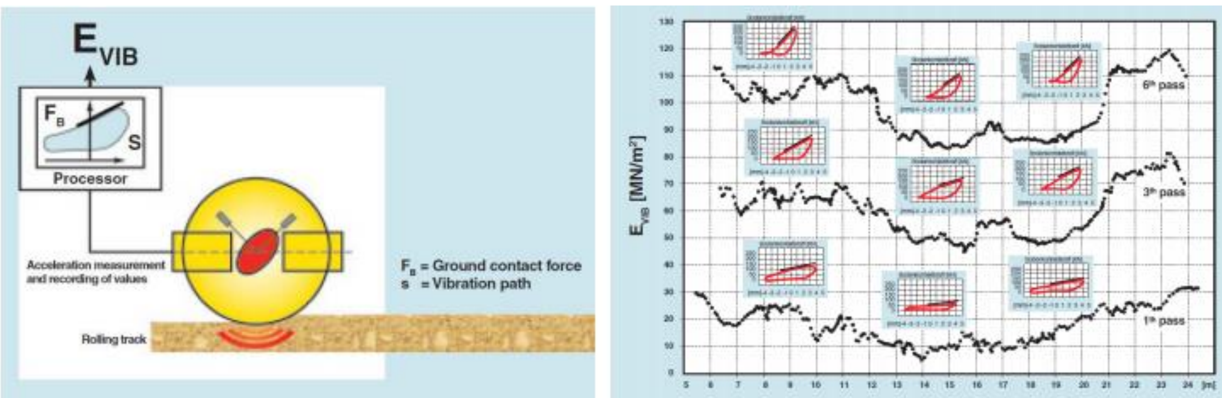

Fig. 7. Monitoring of the E_{vib} parameter [21,22]

When the stiffness of the compacted layer is continuously changed, a wide range of parameters that describe the working regime of the machine varies, such as: the energy required for the vibration process, the moment of the eccentric masses, their positioning, the amplitude and frequency of the vibrations (and implicitly the dynamic force transmitted to the terrain) etc. In the case of compactors of the new generation from the BOMAG company (Figure 8), they are equipped with systems called VarioRoller, later developed as VarioControl, which have the role of changing the direction of the disruptive force of the roller (Figure 9) according to the characteristics of the compacted layer, directly related to the stiffness obtained after each pass of the machine.

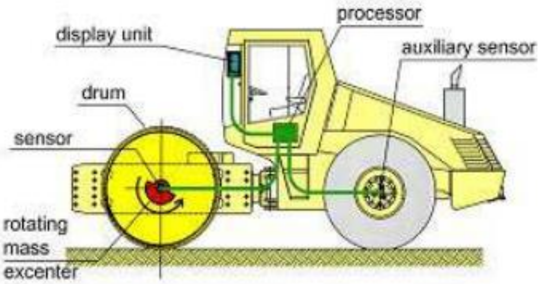

Fig. 8. Equipping with control systems for the compaction process [23]

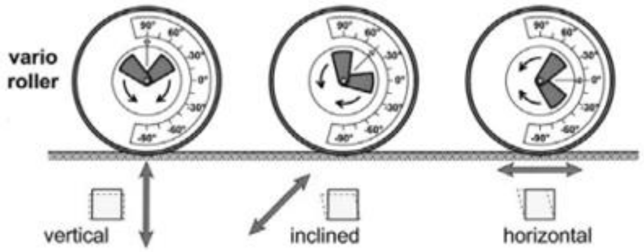

Fig. 9. Changing the direction of action of the exciting force of the vibratory drum [23]

CCC–ACE incorporates a new concept that monitors the variation of ground stiffness during the movement of the compactor on the ground subject to vibration compaction, by monitoring the parameter k_b [N/m]. The relationship for k_b evaluation is:

$$k_b = \omega^2 \left[(m + m_0) + \frac{(m_0 e k_{vario}) cos\varphi}{A_{(z)}} \right], \quad (3)$$

where: where $A_{(z)}$ is the amplitude of the displacement and φ is the it's angle of phase; m and m_0 represent the vibratory drum mass, and, respectively, eccentric masses. The dimensionless index k_{vario} is used for a reduction of the dynamic excitation.
MDP (Machine drive power) implemented a new technology for evaluating the degree of compaction of a layer, patented by CAT and implemented on Caterpillar B-Series compactors (Figure 10). The method consists in monitoring the driving power of the machine by measuring the rolling resistance during compaction, by continuously correlating the vibration parameters of the roller with the characteristics of the layer [24, 25].

Fig. 10. MDP technology [24]

Thus, this method directly measures the stiffness of the ground. Its application is recommended for evaluating the degree of compaction of all types of soil (cohesive and non-cohesive), measuring the stiffness of layers between 30-60 cm thickness.

SCV (Sound Compaction Value) is an evaluation index of the noise recorded during compaction, used mainly to evaluate the progress of the compaction of the base layers of the road infrastructure. The noise detection technique is based on two phases: recording and then analyzing the acquired signal. The principle of noise detection is described in Figure 11, on a compactor with a single vibrating roller.

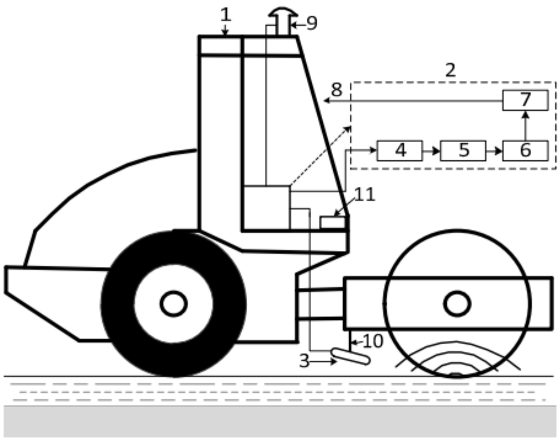

Fig. 11. Scheme of the method of detecting acoustic waves generated during the compaction of filling materials used in road infrastructure [26]:
1. vibrating compactor; 2. noise detection system; 3. microphone; 4. signal conditioning mode; 5. signal acquisition mode; 6. signal processing mode; 7. display; 8. the dashboard of the compactor; 9. GPS receiver; 10. the microphone holding system; 11. battery.

Depending on the change in the structure of the layer, its behavior also changes during the dynamic action of the vibrating roller, generating noise that has different acoustic pressure when the stiffness of the layer changes (Figure 12). The working principle of the evaluation of the SCV index is presented in Figure 13.

Finally, a classification can be made of all the methods applied to evaluate the degree of compaction of soils/asphalt mixtures according to the conformity of the results verified by other available methods (laboratory or "in situ" experimental tests).

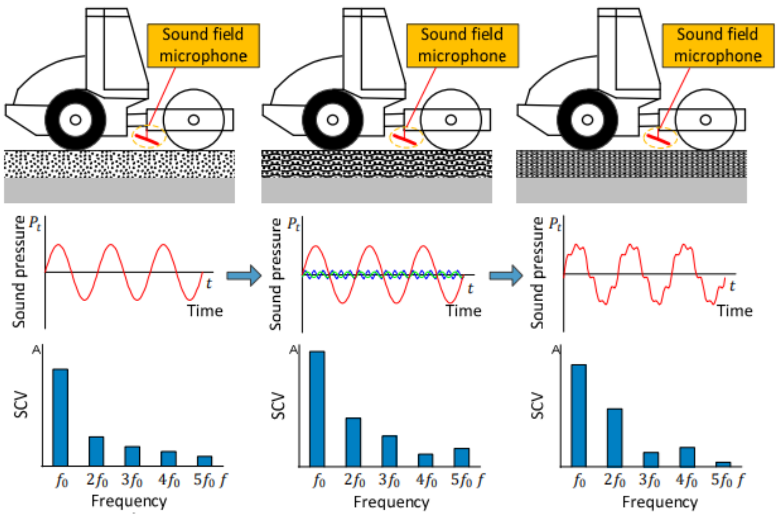

Fig. 12. Illustration of changes in sound pressure and SCV with increasing layer stiffness [26]

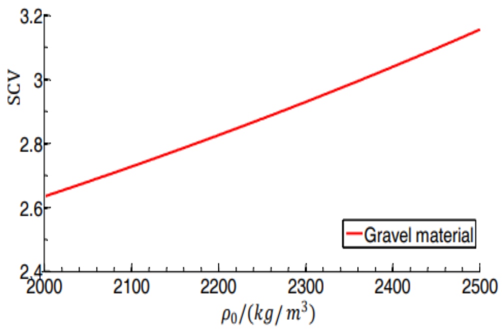

Fig. 13. SCV index vs. dry density of the compacted material [26]

Thus, five levels of acceptability are distinguished, used in the specialized literature [27] in the field of compaction identified according to the constitutive type of the calculation model adopted and the degree of precision of each of the measured, monitored and processed data (Table 3).

Table 3: The five levels and their degree of accuracy accepted for evaluation of the vibratory roller compaction process

No	Level description		Measured parameter	Application S	Application MA	Accuracy	Model type
1	Empirical models based on frequency response of drum vibrations		Harmonics ratio (*CMV*, *RMV*, *CCV*)	X	X	Weak	N/A
	Empirical models based on frequency response of drum oscillations		Harmonics ratio (*CCC*)	-	X	Weak	N/A
2	Energetic empirical models based on rolling resistance response of drum		Energy index (*MDP*)	X	-	Weak	Dynamic/ static
3	Simplified static mechanistic models	Layered half-space models Discrete elements models: Kelvin-Voigt, Maxwell, Zener, Burgers etc.	Stiffness, modulus, rolling force (E_{vib}, K_s)	X	X X	Satisfac-tory	Dynamic
4	Dynamic models		Modulus, rolling force (*VCV*)	X	-	Good	Dynamic
5	Dynamic models with artificial intelligence		Estimated modulus, estimated density (M_{NN}, r_{ODMS})	- X	X X	Excellent	Dynamic

Note: S – soil: MA – asphalt mixture.

4. Conclusions

In general, the prediction methods (implemented in control systems) are mainly based on linear and/or non-linear regression in order to predict the degree of compaction and compaction state of the soils or asphalt mixtures. Thus, a lot of papers shows results of good practice to use CCC/IC technology for prediction of the compaction of the filling materials and, by interpolation, compactness of the entire working area.
Summarizing the above presented, it can observe that the factors that affect the compaction effect of soils and asphalt mixtures are divided into internal and external factors. Thereby, the internal factors mainly include material characteristics and the strength of the underlying layer, then, the external factors consist of compaction parameters of working regime, compaction energy, constructive drum variant of machinery, compaction mode (static or dynamic), and compaction technology (taking account by machine velocity, number of passes etc.).

References

[1] NE-008-97: Regulation regarding the improvement of weak foundation land through mechanical procedures (Normativ privind îmbunătăţirea terenurilor de fundare slabe prin procedee mecanice).
[2] STAS 8942/3-90: Foundation land. Determination of the linear deformation modulus by field tests with the plate (Teren de fundare. Determinarea modulului de deformaţie liniară prin încercări pe teren cu placa).
[3] NP 125:2010: Regulations regarding the foundation of constructions on soils sensitive to wetting (Normativ privind fundarea construcţiilor pe pământuri sensibile la umezire).
[4] STAS 9850-89: Land improvement works. Checking the compaction of embankments (Lucrări de îmbunătăţiri funciare. Verificarea compactării terasamentelor).
[5] STAS 3300/2-85: Foundation land. Calculation of the foundation land for direct foundation (Teren de fundare. Calculul terenului de fundare în cazul fundării directe).
[6] Debeleac, C. "On the efficiency of compacting equipment." *The Annals of "Dunarea de Jos" University of Galati* 2, no. XVI, Fascicle XIV Mechanical Engineering (2010): 51-54.

[7] Dobrescu, C.F. "Analysis of the dynamic regime of forced vibrations in the dynamic compacting process with vibrating roller." *Acta Technica Napocensis* 2, no. 1 (2021): 71 – 76.
[8] Debeleac, C., and S. Năstac. "On Non-linear Characteristics Evaluation of Vibratory Tool and Terrain Interaction for Embankment Works*." Proceedings in Applied Mathematics and Mechanics - PAMM* 12, no. 1 (2012): 605–606.
[9] Bratu, P., and C. Debeleac. "The analysis of vibratory roller motion." Paper presented at the VII International Triennial Conference Heavy Machinery – HM 2011, Vrnjačka Banja, Serbia, June 29–July 2, 2011.
[10] Debeleac, C., A. Buraga, and S. Năstac. "Nonlinear analysis of the terrain layers response at vibrating compaction process." Paper presented at the 27rd International Congress on Sound & Vibration (ICSV27), Online, July 11-16, 2021.
[11] Leopa, A., C. Debeleac, and S. Nastac. "Simulation of Vibration Effects on Ground Produced by Technological Equipments." paper presented at the 12th International Multidisciplinary Scientific GeoConference SGEM 2012, Albena, Bulgaria, June 17–23, 2012.
[12] Debeleac, C., S. Nastac, and A. Buraga. "On nonlinear dynamics of vibrating compaction process of construction materials." Paper presented at the 26th International Congress on Sound and Vibration (ICSV26), Montreal, Canada, July 7-11, 2019.
[13] Debeleac, C., and S. Năstac. "Stochastic Approaches of Nonlinear Model-Based Simulations for Vibratory Compaction Process." Paper presented at the 85th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM), Erlangen, Germany, March 10 - 14, 2014.
[14] ECON Technologies Co., Ltd. "Dynamic Signal Analyzer." Accessed November 29, 2022. https://www.econ-group.com/en/productshow33.html.
[15] Benstone Instruments Inc. "Portable Sound & Vibration Analyzers. impaq Pro Portable Vibration Analyzer." Accessed November 28, 2022. https://www.benstone.com/tm/?mode=product&mid=1&id=31&name=impaq-Pro-portable-vibration-analyzer.
[16] National Instruments. "Sound and Vibration." Accessed November 29, 2022. https://www.ni.com/ro-ro/shop/hardware/sound-and-vibration-category.html#.
[17] Asphalt Pavement Association of Oregon. Accessed November 14, 2022. http://www.apao.org/presentations/past-asphalt-conferences/intelligent-compaction-technology-discussion.pdf.
[18] Ma, Yuan, Yang Zhang, Wei Zhao, Ximao Ding, Zhiwen Wang, and Tao Ma. "Assessment of Intelligent Compaction Quality Evaluation Index and Uniformity." *Journal of Transportation Engineering, Part B: Pavements* 148, no. 2 (June 2022): 04022024.
[19] Anderegg, R. "ACE AMMANN Compaction Expert." Technical Paper, Ammann. Verdichtung AG, Langenthal, Swiss.
[20] Vennapusa, P. K. R., D. J. White, and M. D. Morris. "Geostatistical analysis for spatially referenced roller-integrated compaction measurements." *Journal of Geotechnical and Geoenvironmental Engineering* 136, no. 6 (2010): 813–822.
[21] Kelm, M. *Numerical simulation of the compaction of non-cohesive soils using vibratory rollers / Numerische Simulation der Verdichtung rolliger Böden mittels Vibrationswalzen*. Dissertation. Technische Universität Hamburg-Harburg (TUHH), 2004.
[22] Briaud, Jean-Louis, and Jeongbok Seo. "Intelligent Compaction: Overview and Research Needs." December, 2003. Accessed November 15, 2022. https://intelligentconstruction.com/downloads/PapersReports/Texas_Briaud_IC%20Report_200409.pdf.
[23] Bekker, M.G. *Introduction to Terrain-Vehicle Systems*. Ann Arbor, Michigan, USA, University of Michigan Press, 1969.
[24] Chang, George. "Fundamentals of Intelligent Compaction." May 3, 2012. Accessed November 16, 2022. https://es.slideshare.net/gkchang/fundamentals-of-intelligent-compaction/12.
[25] Lee, Soomin, Abubakar Sharafat, In Sup Kim, and Jongwon Seo. "Development and Assessment of an Intelligent Compaction System for Compaction Quality Monitoring, Assurance, and Management." *Appllied Science* 12, no. 14 (2022): 6855.
[26] Zhang, Qinglong, Tianyun Liu, and Qingbin Li. "Roller-Integrated Acoustic Wave Detection Technique for Rockfill Materials." *Applied Sciences* 7, no. 11 (2017): 1118.
[27] Donghai Liu, Youle Wang, Junjie Chen, and Yalin Zhang. "Intelligent compaction practice and development: A bibliometric analysis." *Engineering*, *Construction and Architectural Management* 27, no. 5 (2020): 1213-1232.