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Research paper

Modeling the vibratory roller compaction process of road soils

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Abstract: Road infrastructure is aimed to be sustainable construction in today's condition of heavy traffic. Depending on geotechnical characteristics of soils there are chosen adequate techniques for compaction, meaning: type of compaction, equipment, compaction parameters and, if possible, computer aided acquisition and processing of data. This paper presents research results on the vibratory roller compaction process of road soils, from the point of view of process mathematically modeling and statistically modeling of process parameters interdependence. The obtained regression model is innovative one and fit for further application in optimization (by AI and IoT) of the compaction process. Good correlation of all the results (self-pulsation values) proves the adequate assumptions for both modeling and experimenting. Further development of this research is intended to develop a special software for direct correlation of road geographical position and soil characteristics to the compaction process parameters optimum values.

Keywords: vibration, compaction process, road soil, modeling, regression

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1. Introduction

The basic element of road infrastructure is soil and special attention is to be given on the way it is compacted and how the degree of compaction (98%) is to be maintained over time, in various geo-climatic and estimated traffic conditions. One solution [1] for reinforcement of road soils and reducing their deformation if repairing or maintenance are to be done, is that of using sand-filled piles. The best solution is nevertheless that of correct soil compaction.

If the compaction process is adequate then its positive effects would be of increasing soils' volumetric weight, shear strength and deformation modulus so that the specific stabilization subsidence of the soil layers is obtained. Soils compaction is defined [2] as the physic-mechanical process going on under exterior mechanical loading. It results in overlapping of solid phase particles on the assumption that liquid and gaseous phases get reduced in the mineral skeleton composition. Significant decrease of porosity and increase of voids filling are obtained.

In the compaction process there are some soil's characteristics that have important influence on the quality of embankment for any road construction [3]. These are: soil's composition (gravel, sand, silt), granulometry and humidity. The degree of compaction depends on these characteristics and correlated to them represents the most important factor in road construction sustainability. Failure to reach the level of compaction specified in standards, codes, regulations results in [4] the reduction of bearing capacity and loss of embankment stability through major types of deformation (subsidence, landslides).

Depending on how the compaction loading is applied over the soil, there are two major types of [5] compaction processes: static and dynamic.

In static compaction the pressure is generated by a roller, or a pneumatic tire rolling forward and backward over the soil layer.

In dynamic compaction the vibrations are transmitted to the soil layer under compaction and thus, relative displacement and more compact rearrangement of particles occur. Depending on the way compaction force is applied over the soil, there are two kinds of dynamic compaction techniques, mentioned next.

a. The dynamic vibratory compaction is the technique in which periodic vibration oscillations are transmitted by a roller to the soil layer to be compacted. There can be achieved higher densities of soil's granules with greater depth effect than in static compaction. Final degree of compaction and, implicitly, final density can be achieved in fewer passes. The vibratory compaction if fit for nonhomogeneous and noncohesive materials (ex.: sand, gravels);
b. The dynamic impact compaction is the technique in which a defined weight mass falls down from a certain height on the soil layers. Thus, compaction occurs under the action of impulses transmitted to the material through periodic compression waves caused by shock. The impact force generates pressure waves underground that determine high pressure in depth of soil layers.

Basic aspects of intelligent compaction technique applied in road construction are discussed in [6]. There are detected vibrations generated by compaction rollers, analyzed and measurement parameters calculated so that their values to represent the stiffness or compactness of the soil layers. These parameters are: Compaction Meter Value (CMV), Compaction Control Value (CCV) and Resonant Meter Value (RMV). Their values are calculated aided by Fourier analysis (Fast Fourier Transform) of the vibration signals obtained from various combination of amplitude and frequency values of the rollers when the speed value of the compaction equipment is set to the optimized value.

A study on dynamic model of vibratory roller – soil, as two degree of freedom model in compaction process is presented in [7]. Two main steps of research are mentioned, meaning: the consistency of dynamic model with the in-situ condition and the correct simplification of the model so that to have as simple as possible calculation method. Mainly, it is assumed that the effect of vibratory roller on the soil can be accurately enough equivalent to a system made of mass – spring – damper.

In road construction it is important to know the soil type and its characteristics, so that to adequately establish the work steps and procedure for efficient and sustainable road infrastructure. Also, for example, knowledge on rheological properties of paste used in mixtures added to self-compacting concrete is important for road construction efficiency [8].

The soil is a complex system by itself, rather considered as rheological system [9] and influenced by: structure; answer to various loads applied; temperature environments; previous behavior under stress. The study of compaction process is done considering the soil as an infinite, homogenous and isotropic space whose basic properties are: elasticity, plasticity and viscosity. There are different rheological models associated to the description of soil behavior while the compaction process is on. The most frequently used are: Voigt–Kelvin [10], Bathelt, Hartman, Maxwell. These ones are complex models and are deduced from the combination of basic models: Hooke, Newton, Saint–Venant and Bethelt.

For example, research results on dynamic compaction of soils under forced vibrations controlled regime (Voigt–Kelvin rheological model) are presented in [11]. The amplitude curves, $A = X_0(\omega, k)$, variation on vibratory pulsation, ω, and soil rigidity, k, prove that each pass of the vibratory roller over the soil layer results in higher values of rigidity. This is why the resonance peaks move towards higher values of pulsation and the corresponding amplitude resonance values get higher.

Modeling compaction process and soil behavior when interacting with the vibratory roller is basically done by rheological models. An example of modeling the viscoelastic soil's behavior by Voigt-Kelvin and Maxwell rheological models is also shown in Fig. 1 [12].

In order to determine the optimum value for the compaction frequency of the plate and rollers, there has been carried out research on granular soil and results presented in [13]. Some relevant conclusions with real practical application are as follows: if considering the average densification of soil's layer compacted, the vibratory roller optimum frequency should be about coupled roller – soil resonant frequency; there is no significant correlation of the compaction efficiency to the centrifugal force of the roller.

The previous research done by the authors is focused on the compaction process of road soils and the most used model of their behavior is Voigt–Kelvin one. This is due to geographic position (of the country regions) and soils' predominant characteristics as purely viscoelastic space (characterized by viscosity and elasticity coefficients). Not the

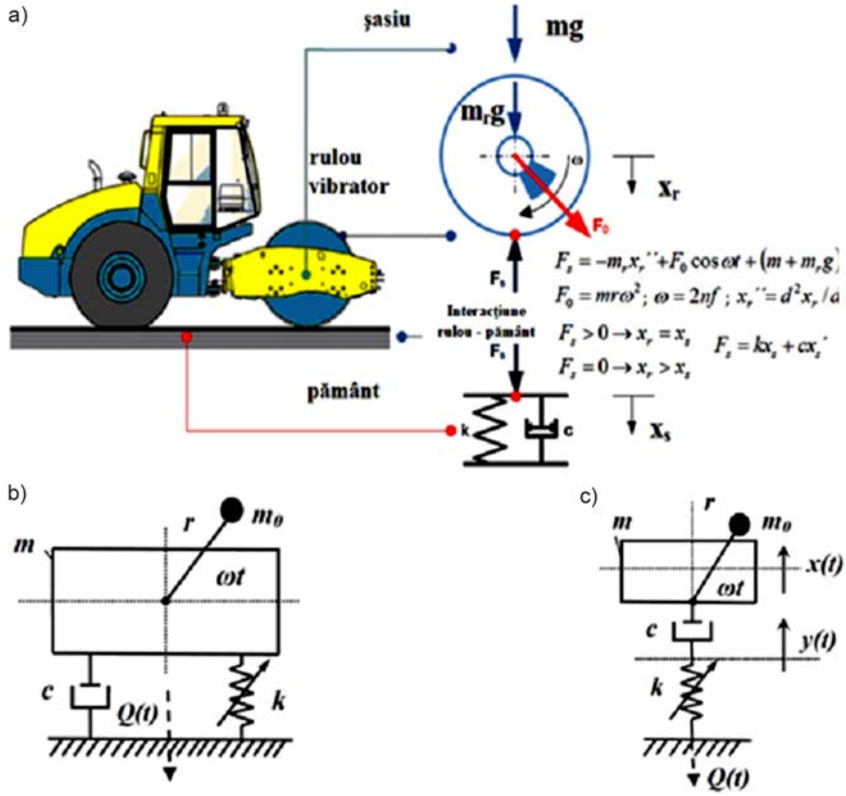


Fig. 1. Rheological models of soils for compaction process modelling: a) modeling the vibartory compaction process, b) rheological model Voigt–Kelvin, c) rheological model Maxwell [12]

least, it is considered the relative simplicity of the assumed model. The fact that previously obtained experimental results [14, 15] are accurate and fit to the modeled one, stands as "proof" of the correct assumption for the Voigt–Kelvin model.

Studying the compaction process interdependence parameters (input and output variables) is important as, similarly to any process, it is assumed that good knowledge on how it works determines adequate results. Basically, if the road soils compaction process is correct, the road infrastructure would be sustainable and no problems for vehicles driving on would be on medium and long time.

This paper is aimed to present some relevant research results on the vibratory compaction process of soils for sustainable road infrastructure. There are some basic assumptions for this research, as mentioned next:

a) permanent contact of the vibratory roller and the soil, while the compaction process is on;
b) compaction process consists of sequences of short time elementary compaction processes going on at a single pass of the vibratory roller;

c) soil is considered elastic medium at small subsidence and there is a constant value for soil stiffness coefficient while each elementary process (at each pass);
d) there is overlapping and accumulation of the elementary compaction processes effects, in time and locally, so that the whole compaction processes is considered to be discrete, sequential and cumulative.

The innovative aspects of this research refer to the following aspects:
– identification of the geotechnical characteristics of studied soils for road construction, both in laboratory and in-situ conditions so that to define the input data, soil type;
– developed software for mathematical modeling of soil – vibratory roller interaction;
– statistical modeling of the soil compaction process – by regression model with two inputs variables and one output variable;
– comparison of the results obtained by the two type models (mathematically, based on theoretical and statistically, based on experimental data);
– estimation of further research development based on to the research results.

2. Research method

Typical characteristics of the studied soil have been determined so that to set assumptions for this research. The determination was done by laboratory tests, according to specified standard procedures for geotechnical determination of soil properties. This is how the methods used in research are closely related to the specificity of the studied soil. Relevant results are evidenced as follows.

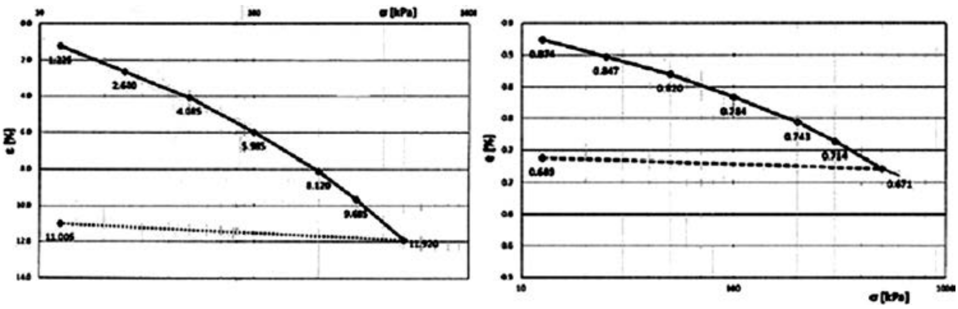
Granulometry tests resulted in dusty/silt gravel with sand (46% gravel, 24% sand, 22% dust/silt and 8% clay), the soil being non-cohesive one. The granulometric determination was done in conformity Romanian SREN ISO 14688-2/2018, the equivalent of EN ISO 14688-1:2018 standard [16]. The soil sample was taken in-situ.

Oedometer test done in order to determine compressibility characteristics by successively progressive loading, σ_i, and then unloading of the soil sample (in the oedometer cell) while measuring the resulting deformation, ε_i. The procedure is a standard one according to Foundation Soil. Earths Compressibility Determination by Oedometer Testing, STAS 8942/1-89 (the Romanian standard in use for certification and validation of geotechnical tests) [17].

The sample was taken from undisturbed soil sample, with a mass of approximately 4 kg. Plotted graphs, based on equipment software (ACE EmS) and the experimental results evidence the characteristic curves: specific subsidence depending on load stress and pores index depending on load stress (see Fig. 2).

The *compaction equipment* used in experiments is BOMAG BW 213 D-5 with one vibratory roller.

Based on preliminary experiments in this research [13], the values of vibratory compaction process parameters were set to:
– vibration frequency – within the interval 30÷33.8 Hz;
– vibration amplitude – could be continuously varied, but for each experiment (single pass) it has been considered a constant value – within the interval 1÷1.5 mm;
– driving speed – constant (optimized) value of 2.2 km/h.



(a) (b)

Fig. 2. Oedometer test plots: (a) specific subsidence vs. load stress graph, (b) pores index vs. load stress graph

The experiments were done on Transilvania highway (in Romania) and a special testing polygon was available. The length for each pass was about 50.00 m, with two lanes of about 4.00 m each.

The degree of compaction was determined as the ratio of dry volumetric weight, determined in laboratory or in-situ versus maximum dry volumetric weight determined in laboratory for samples taken in-situ. The desired value for the degree of compaction is 98%. It was obtained, mainly, after the fifth pass.

An innovative aspect of studying the vibratory compaction process is that of statistically processing the experimental data and obtaining representative regression model (identified by correlation coefficient square value, R^2, close to 1). This is done in order to determine adequate relationship of the parameters specific to compaction process of road soils. The studied data were obtained from the experiments mentioned above.

There are some steps to take for statistical modeling method as follows next.

Selection of the adequate design of experiment program was done based on the available statistical software (free version DOE Pro) and on the number of variables considered for modeling. The applied design of experiments is Central Composite Design (CCD) and the variables studied are:

– two input variables:
  - A – vibrations amplitude with values within the interval 1.08 mm; 1.34 mm;
  - $\nu(f)$ – vibrations frequency with values within the interval 30 Hz; 34 Hz;
– three variation levels for each of the input variable (minimum, medium, maximum);
– number of experiments: 10;
– number of replicates: 5;
– software: DOE Pro XL [18];
– one output variable: K, degree of compaction [%].

The advantage of CCD design is that requires a reduced number of experiments and replicates, the software indicating the input variables (coded) values and their combination for each experiment.

If the notation of real (natural) input variable is z_i, then the coded variable notation would be x_j, with the interdependence relation given by relation (2.1):

$$x_j = 2\frac{z_j - \overline{z}_j}{z_{\max} - z_{\min}} \tag{2.1}$$

where: $\overline{z}_j$ is the average value of z_j variable, $\overline{z}_j = \dfrac{z_{\min} - z_{\max}}{2}$; $z_{\min}$; $z_{\max}$ – minimum, respectively, maximum values of z_j variable

3. Dynamic analysis of the vibratory roller

Data acquisition for the vibrations of the compaction roller was performed in-situ, aided by uni-axial sensor for vibration measurement connected to analogue input module, from National Instruments (Fig. 3). The data acquisition board is USB NI 9233, 4 channels, analogue input. The accelerometer sensor is miniature triaxial piezoelectric 4506 B 003, Brüel & Kjaer.

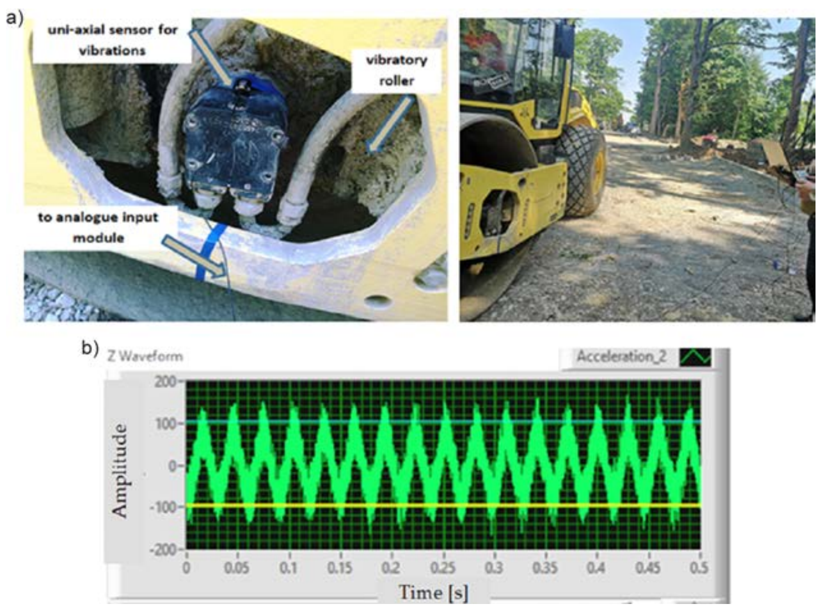


Fig. 3. Experiments and data acquisition: a) in-situ experiments, b) vibration acceleration data acquisition

The focus of this research was to analyze interaction of the vibratory roller with the soil layer to be compacted, by vibration of the drum. For different discrete values of the roller (drum) vibration frequency, there were measured specific parameters of the vibrations transmitted to the layer under compaction, such as: acceleration, speed and amplitude. Each of these measurements was done for different passes of vibratory roller over the soil layer to be compacted. Aided by equipment software (that involves Fourier Transformation) the data are processed so that, for example, it results the maximum acceleration value of 48.73 m/s^2 for the 33.8 Hz frequency of vibratory roller vibrations.

Further processing of the experimental data is aimed to compare these results to the ones obtained by mathematical modeling of the compaction process. In order to mathematically model the compaction process, it has been considered the interaction of vibratory roller –soil similar to the simplest one, that of two purely elastic elements (Fig. 4). This is due to the fact that differences in self-pulsation (frequency) values, when compared to the Voigt Kelvin model, are less than 5% – see also [14].

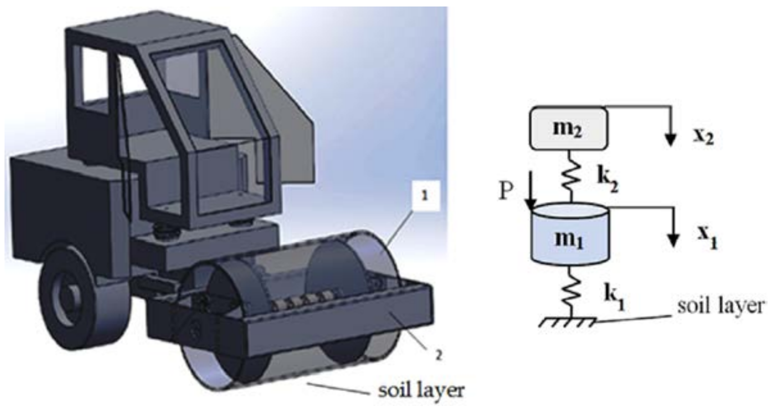


Fig. 4. Scheme of the vibratory roller – soil layer interaction; 1 – vibratory roller; 2 – front chassis

The calculus hypotheses for this two degree of freedom model are:

– elastic connection of the vibratory roller to the front chassis;
– the soil layer for compaction is modeled as elastic element;
– while the compaction process is on, there is permanent continuous contact between the roller and the soil layer.

The significance of notations used for mathematically modeling vibratory roller – soil layer interaction is:

– vibratory roller mass, m_1; equipment's front chassis mass, m_2;
– stiffness coefficient of soil, k_1; stiffness coefficient of elastic connection of the vibratory roller to the front chassis, k_2;
– system's general coordinate for absolute strain related to soil, x_1; system's general coordinate for absolute strain related to chassis, x_2;
– excitation vibration force, P

$$P = P_0 \sin \omega t \tag{3.1}$$

– amplitude of the excitation force, P_0;
– pulsation of the periodic excitation, $\omega(2\pi\nu)$ and frequency of periodic excitation, ν.

As the vibratory compaction process is due to forced vibrations (excitation), there can be deduced [15] the matrix motion equation as:

$$M\ddot{x} + Kx = f \tag{3.2}$$

where: M – stands for the inertia matrix, symmetric and nonsingular; K – stiffness matrix; f – the excitation force vector; x – displacement vector.

$$f^T = [P0\ldots0] \tag{3.3}$$

If the solution of relation (3.3) is:

$$x_j = A_j \sin \omega t \quad (j = 1, \ldots, 4) \tag{3.4}$$

then, it results the vibration amplitude, A_j, as solution of an algebraic equation system for stationary vibrations. Solving this system is more convenient [19] when aided by the dedicated program, PULS-AMPL – developed by the authors in AppDesigner, Matlab.

There were carried on experiments of soil compaction, with different values for vibration frequency in different (single) passes over the compaction soil layer. For example, at the second pass (meaning not too compact soil), the vibration amplitude plots and values are shown in Fig. 5. These experimental measured values were compared to the ones resulted by modeling as two purely elastic elements interaction and calculated aided by PULS-AMPL (Fig. 6). As it can be, the results for the vibratory roller self-pulsation are:

$$\omega_1 = 23.775 \text{ [rad/s]}; \quad \omega_2 = 53.906 \text{ [rad/s]};$$
$$\omega_3 = 114.539 \text{ [rad/s]}; \quad \omega_4 = 164.926 \text{ [rad/s]}$$

Analyzing the results obtained both experimentally and mathematically modeling (computer aided by PULS-AMPL) there is the conclusion of good correlation between these results, as follows:

- experimental self-frequency value is 29.88 Hz, the self-pulsation pulsation (angular frequency) value is 187.646 rad/s; mathematical modelling (PULS-AMPL program) resulted in self-pulsation value of 164.926 rad/s;
- the two mentioned values for vibratory compaction process are, relatively, close – with relative error of 13.78%.

Based on the above presented results, the assumptions of adequate experimental and modeling is estimated to be right. As for the other values for self-pulsations, generated both experimentally and by mathematically modeling, the deviation of experimental from theoretical could be explained by parasitic signals introduced in the data acquisition system, that could not be completely adjusted or removed.

One further step in this research is that of statistically modeling and obtaining the regression model of vibratory roller compaction process, for the variables interaction (see also section 2. Research Method).

For the considered compaction process, according to relation (2.1), the coded variables are:

$$x_1 = 2 \cdot \frac{A - 1.34}{0.52} = 3.846(A - 1.34); \qquad x_2 = 2 \cdot \frac{v - 32}{4} = 0.5(v - 32) \tag{3.5}$$

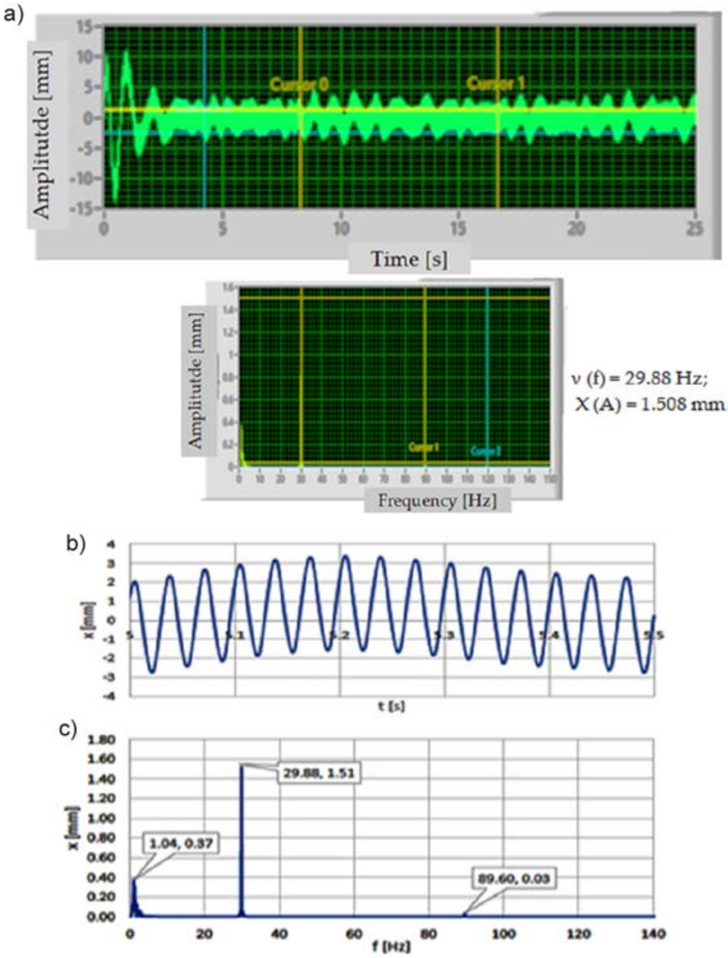


Fig. 5. Data acquisition – experimental results: (a) online data acqusition results, (b) data without parasitic osicilations, c) resonance frequencies

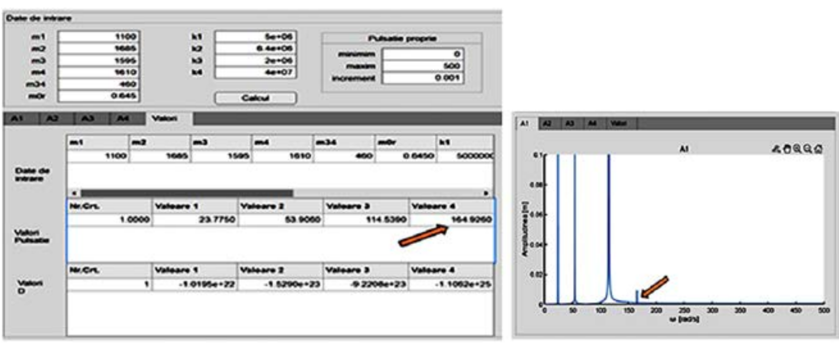


Fig. 6. PULS-AMPL modeling results

while the experiment design matrix (transposed), X^T is:

$$X^T = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ -1 & -1 & 1 & 1 & 0 & 0 & -1 & 1 & 0 & 0 \\ -1 & 1 & -1 & 1 & 0 & 0 & 0 & 0 & -1 & 1 \end{pmatrix} \tag{3.6}$$

The experimental results for CCD are shown in Table 1.

Table 1. CCD values

Factor	A	B	Degree of compaction (K) replicates					K (average value) [%]
Row	Amplitude A [mm]	Frequency ν [Hz]	$K1$	$K2$	$K3$	$K4$	$K5$	
1	1.08	30	83.45	82.8	85.02	83.2	82.23	83.34
2	1.08	34	99.78	99.50	99.37	99.54	99.51	99.54
3	1.6	30	93.24	92.32	92.1	90.9	92.84	92.28
4	1.6	34	93.78	93.98	95	94.8	93.14	94.14
5	1.34	32	94.17	94.98	95.34	95	95.91	95.28
6	1.34	32	95.74	95.97	96.2	96.2	96.09	96.04
7	1.08	32	93.8	92.98	94.4	94.8	96.02	94.4
8	1.6	32	95.99	96.08	97.4	96.98	97.95	96.88
9	1.34	30	88.86	89.87	90.88	91.12	90.37	90.22
10	1.34	34	95.79	96.08	96.84	96.64	97.05	96.48

Regression analysis aided by DOE Pro XL software resulted in (Fig. 7):

– adequate model, with 0.9532 correlation coefficient square value;
– input variables (A, ν) significantly influencing the output variable (K).
– second order input variables (A^2, ν^2) do significantly influence the output, in case of frequency and do not significantly influence it, in case of amplitude.

Factor	Name	K, degree of compaction Coeff	P(2 Tail)	Tol	Active
Const		95.911	0.0000		
A	A, amplit	0.92000	0.0000	1	X
B	v, freq	4.137	0.0000	1	X
AB		-3.710	0.0000	1	X
AA		-0.52286	0.0848	0.9722	X
BB		-2.813	0.0000	0.9722	X
	R^2	0.9532			
	Adj R^2	0.9478			
	Std Error	1.0127			

Factor	Name	Low	High	Experim
A	A, amplit	1.08	1.6	1.34
B	v, freq	30	34	32

Multiple Response Prediction		99% Confidence Interval	
		Lower Bound	Upper Bound
K, degree of compaction	95.9114	94.052	97.770

Fig. 7. DOE results of the regression analysis, $K = f(A, \nu)$

Based on relation (10) and the DOE results, there are obtained regression models as follows next:

– for coded variables

$$Y = 95.911 + 0.920 \cdot x_1 + 4.137 \cdot x_2 - 3 \cdot x_1 x_2 - 0.523 \cdot x_1^2 - 2.813 \cdot x_2^2 \tag{3.7}$$

– for natural variables

$$K = -1014.93 + 252.57 \cdot A + 56.634 \cdot v - 7.135 \cdot Av - 7.735 \cdot xA^2 - 0.703 \cdot v^2 \tag{3.8}$$

Graphic representation of the response surface is shown in Fig. 8, where it can be noticed the influence of the input variables' values (vibration amplitude, A and frequency, v) on the output variable values (degree of compaction, K).

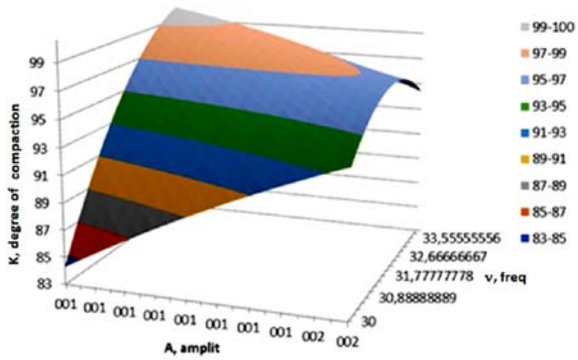


Fig. 8. Response surface, $K = f(A, v)$

Pareto diagram (Fig. 9) evidences how strong the influence of the input variables and their interaction is on the output variable. One can notice the highest influence of vibration frequency on soil layer degree of compaction.

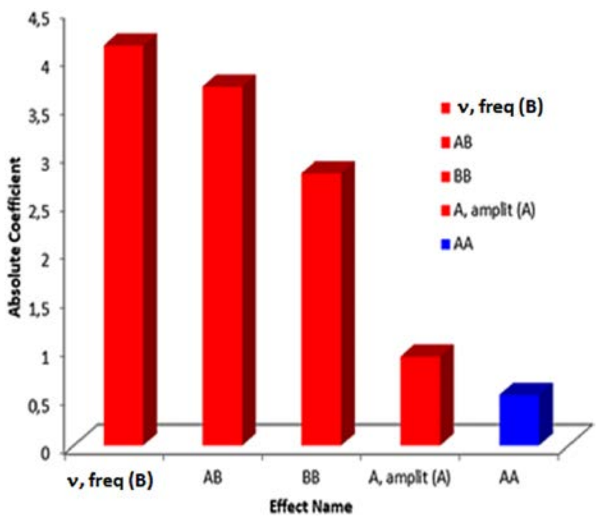


Fig. 9. Pareto diagram

4. Conclusions

Road infrastructure is aimed to be sustainable construction and one important aspect to achieve this goal is that of knowing soil's characteristics and correlated to it, to determine optimum compaction process parameters values.

There are many representative studies on vibration and their effects on civil construction and not the least, on vibration monitoring and their induced risks mitigation. Some examples are as follows: intelligent compaction technique applied in road construction are discussed in [6]; dynamic model of vibratory roller – soil, as two degree of freedom model in compaction process [7].

This paper presents research results on the vibratory roller compaction process of road soils, from the point of view of process mathematically modeling and statistically modeling of parameters interdependence. The obtained regression model is innovative one and is fit for further application in optimization (by AI and IoT) of the compaction process.

There were determined materials' characteristics (soils for road structures) by granulometry and oedometer test. The results were adequate for road infrastructure, as the material is dusty/silt gravel with sand, of adequate coefficient of volume compressibility.

Data acquisition for vibrations transmitted to soil by the compaction roller was performed in-situ, aided by uni-axial sensor for vibration measurement connected to analogue input module, from National Instruments.

In order to mathematical modeling the compaction process, it has been considered the interaction of vibratory roller – soil similar to the one of two purely elastic elements. Solving the system equations was done aided by a dedicated program, PULS-AMPL developed in AppDesigner, Matlab.

Analyzing the results obtained both experimentally and mathematical modeling comes to the conclusion that there is good correlation between these results.

An innovative aspect of studying the vibratory compaction process is that of statistical processing the experimental data and obtaining adequate regression model.

Regression analysis aided by DOE Pro XL software resulted in adequate model, with 0.9532 correlation coefficient square value and input variables (A, v) significantly influencing the output variable (K).

The obtained regression model is innovative one and is fit for further application in optimization (by AI and IoT) of the compaction process. Further development of this work will envisage development of specialized software that would enable direct correlation of road geographical position, soil's characteristics and compaction equipment specifications to the compaction process parameters optimum values.

References

[1] S.M. Ayyad and O. A. Ahmad, "The Use of Sand Columns in the Reinforcement of Weak Layers in Road Engineering", *Archives of Civil Engineering*, vol. 67, no. 1, pp. 527–538, 2021, doi: 10.24425/ace.2021.136487.

[2] Ş. Mihăilescu, et al., *Maşini de Construcţii II. / Machine building*. Bucharest: Printing House Editura Tehnică, 1985.

[3] F. Belc and G. Lucaci, *Căi de comunicaţie terestre. Elemente de construcţie*. Timişoara: Printing House Solness, 2001.

[4] A. Pogany and S. Zdrenghia, "Un procedeu de verificare a compactării terasamentelor prin folosirea cilindrului compactor vibrator / Ein verfahren für überprüfen der bodenverdichtung durch die verwendung der vibrationswalze", in *XVI-a International Conference, "Profesorul Dorin Pavel – fondatorul hidroenergeticii româneşti*. Sebes, 2016, pp. 593–600. [Online]. Available: http://stiintasiinginerie.ro/wp-content/uploads/2016/07/30-77-UN-PROCEDEU-DE-VERIFICARE-A-COMPACT%C4%82RII.pdf. [Accessed: 8 Nov. 2022].

[5] M. Equipment, News and Media, "Metode şi utilaje destinate compactării / Methods and Equipments for Compaction". [Online]. Available: https://www.mequipment.ro/utilaje-si-metode-de-compactare/. [Accessed: 12 Dec. 2022].

[6] L.G. Jadhav and. S.P. Titare, "Intelligent Compaction Analyzer System for Vibratory Road Rollers using ARM Microcontroller and Data Updation on Server using Android Application", *International Journal on Recent and Innovation Trends in Computing and Communication*, vol. 5, no. 8, pp. 214–219, 2017.

[7] S. Li and C. Hu, "Study on Dynamic Model of Vibratory Roller – Soil System", *IOP Conference Series: Earth and Environmental Science*, vol. 113, art. no. 012187, 2018, doi: 10.1088/1755-1315/113/1/012187.

[8] L. He, D. Guangchao, Z. Jingyi, and Y. Yanhai, "Rheological properties of paste for self-compacting concrete with admixtures", *Archives of Civil Engineering*, vol. 68, no. 3, pp. 585–599, 2022, doi: 10.24425/ace.2022.141904.

[9] W. Markgraf, "Rheology in Soils", in *Encyclopedia of Earth Sciences Series*. Springer, 2011.

[10] D. Bartosin, "Non-linear attenuation in soils and rocks", *Proceedings of the Romanian Academy – Series A: Mathematics*, *Physics, Technical Sciences, Information Science*, vol. 7, no. 3, 2006.

[11] C. Dobrescu, "Analiza parametrică reologică a procesului de compactare dinamică a pământurilor în regim controlat de vibraţii forţate", *Buletinul AGIR,* no. 2, pp. 150–155, 2015. [Online]. Available: http://www.agir.ro/buletine/2283.pdf.

[12] S. Bejan and P.A. Heriberto, "Modeling the Dynamic Interaction between a Vibratory – Compactor and Ground", *Romanian Journal of Acoustics and Vibrations*, vol. 12, pp. 94–97, 2016.

[13] C. Wersäll, "Frequency Optimization of Vibratory Rollers and Plates for Compaction of Granular Soil", PhD thesis, Royal Institute of Technology, Stockholm, 2016. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:929931/FULLTEXT01.pdf. [Accessed: 8 Sept. 2022].

[14] D. Căpăţină, C. Niţu, and M. Iliescu, "Research On The Process Of Vibratory Compaction Of Sustainable Roads", *Acta Technica Napocensis – Series: Applied Mathematics, Mechanics, and Engineering*, vol. 63, no. 3, 2020.

[15] D. Căpăţină, C. Niţu, M. Iliescu, "First Elastic Step Vibration Isolation Of Single Drum Vibratory Roller Compactor", *Acta Technica Napocensis – Series: Applied Mathematics, Mechanics, and Engineering*, vol. 65, no. 2S, 2022.

[16] EN ISO 14688-1:2018 Geotechnical investigation and testing – Identification and classification of soil – Part 1: Identification and description.

[17] STAS 8942/1-89 Foundation soil. Earthes compersibility determination by edometer testing.

[18] https://sigmazone.com/doepro_download/. [Accessed: 20 Jan. 2023].

[19] L. Matei and D.I., "Smart Signalization and Public Transport Priority, a First Step to Smart Mobility in a Smart City", *Applied Mechanics and Materials*, vol. 880, pp. 383–388, 2018, doi: 10.4028/www.scientific.net/AMM.880.383.

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