IOSUD – „DUNAREA DE JOS” UNIVERSITY OF GALATI

Doctoral School of Mechanical and Industrial Engineering

DOCTORAL THESIS

- SUMMARY -

ANALYSIS OF THE PERFORMANCE LEVEL OF THE PROCESS OF COMPACTION BY VIBRATION OF CONSTRUCTION MATERIALS AT IMPLEMENTATION

PhD Student,

Eng. Andrei BURAGA

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Series I 6: Mechanical Engineering No. 75

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Braila, *Eng. Andrei BURAGA*
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Keywords: vibration compaction, weak cohesive soil, implementation, analysis, performance level, estimation, degree of compaction, number of passes

CONTENT

Introduction

The opportunity of the doctoral thesis falls within the current context, of the tendency to maximize the operational efficiency of the activities in the field of road construction, by expanding the concerns in finding solutions to achieve the compaction of the land or foundation layers of the road systems by putting compactors into operation with vibrating rollers capable of performing at a quality level imposed by the technological process.

Consequently, the behavior of weakly cohesive soils under the action of compaction machines (in static and dynamic mode) was analyzed in order to achieve the level of performance imposed in accordance with the technical documentation of the respective work.

The purpose of this doctoral thesis consists in the design of theoretical and rheological models to be the basis of the analysis of the soil compaction process by knowing the defining parameters for estimating the evolution of the state of the terrain according to the number of passes of the machine.

Hereby, the main objectives are:

a) identification of the current criteria and requirements regarding the monitoring and quality control of the execution of vibration compaction works;

b) the systematization of the methodologies for carrying out laboratory and in situ tests to identify the initial state of the terrain (from the category of weakly cohesive soils), as well as the degree of compaction achieved after an imposed number of passes. The documentary references were based on the specific standards and norms applicable in the field of soil compaction, as well as the results of the test reports and tests carried out on weakly cohesive soils from Romania within the ICECON S.A. Research Institute. Bucharest and the Geotechnical Laboratory within INCERC Bucharest;

c) implementation the concept of an interactive model in the technological process of working with compactors (static or vibratory), through a qualitative estimation of the performance of the compaction process;

d) identifying the correlations between the evolutions of the defining parameters for evaluating the performance of the compaction process, by establishing approximation laws between them (based on the initial geotechnical tests and the experimental ones carried out during the implementation of the exemplified compaction processes);

e) developed of calculation models with the help of which to analyze the response of the terrain subjected to static and dynamic actions during compaction, with applicability for weakly cohesive soil, with the assessment of settlement, stiffness, longitudinal modulus of elasticity, degree of compaction etc.

The doctoral thesis is composed of six chapters, bibliography and list of works.

Chapter 1 entitled *The current stage of research in the field of the vibration compaction process* presents aspects about the efficiency of the vibration compaction process, by correlating the characteristics of the terrain with the working regime of the compactor, modifying its technological factors.

In **chapter 2**, called *Automation of control and ensuring the quality of the compaction process through monitoring and digitization*, aspects are presented regarding the current criteria and requirements about the monitoring and quality control of the execution of vibration compaction works, by exemplifying some methods and techniques implemented by renowned companies in the field on vibratory compactors. Also, in this chapter, the concept of digitization of the Romanian industry in the context of *Industry 4.0*, in terms of road construction, is also detailed.

Chapter 3 is entitled *Methods of analysis of the compaction process through laboratory and "in situ" investigations of soils used for road foundations*, and the author briefly describes the test methods in laboratory and in situ conditions, highlighting the measured/determined parameters (dry density, moisture, longitudinal static modulus, specific pressure, compaction effort, degree of compaction) that have an impact on the evaluation of the performance of the compaction process of weakly cohesive soils in Romania.

In **chapter 4** *entitled "In situ" experimental evaluation of the static and dynamic compaction process*, the experimental determinations carried out to identify the evolution of the soil condition during compaction are described, together with the database with interparametric laws useful for the global characterization of the compaction performance.

Chapter 5 called *Rheological modeling and simulation of roller-soil interaction* includes a theoretical model and a varied range of rheological models proposed for the modeling and numerical simulation of vibration processes specific to compaction highlighting the response of weakly cohesive soils to harmonic dynamic excitation by estimating the settlement, the degree of compaction, the stiffness of the land, the amplitude of the roll movement, either by the number of passes or in time.

Chapter 6 contains the final conclusions, personal contributions as well as future research directions.

The research works were carried out within INCERC Bucharest and ICECON Bucharest, in the thesis using the experimental results belonging to these research institutes.

1. Current state of research in the field of vibration compaction process

Viewed from a technical and economic point of view, mechanical compaction represents one of the most common and effective methods for changing the characteristics of the terrain, which manifests itself through changes in its structure (by increasing the density as a result of the decrease in the volume of pores containing air and the resettling of the particles in its composition) with a visible result in the modification of its characteristics in terms of resistance, deformability and permeability, all of which are obtained as an effect of the input of mechanical energy applied with specialized technological equipment [1 – 3]. Moisture is one of the factors with a significant influence on the results of the compaction process. The optimal compaction moisture is thus distinguished as the water content corresponding to obtaining the highest density result at a specific compaction effort. The fundamental principles of soil compaction were developed in 1933 by Proctor during the studies carried out for the construction of dams in Los Angeles (USA), in order to establish solutions regarding the behavior of soils with unstable structures [10]. Proctor demonstrated that the dry density of soil depends on moisture, compaction effort and soil characteristics (granularity, mineralogy, uniformity). The original method (appeared in 1958) refers to the normal Proctor test, being updated by developing the modified Proctor test. The description of the test methods developed by Proctor were first mentioned in the ASTM and AASHTO standards. Following the research carried out, it was found that there is an 8% difference in the dry density values obtained on compacted clayey sand samples, respectively 10% in the case of dust samples. It was also observed that as the compaction effort increases, depending on the applied methodologies, the efficiency of the mechanical compaction process occurs, the variations of compaction characteristics obtained being in the range of 8-11%.

Currently widely applied are the provisions of ASTM D698 "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort" and AASHTO T99 for the normal Proctor test and ASTM D1557 "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort" and AASHTO T180 for modified Proctor test. At the international and national level, the specialized literature reflects intense concerns regarding qualitative and quantitative parametric analyzes of the compaction process in regime controlled by technological factors, especially regarding compaction energy and correlation with compaction characteristics [15-17]. Thus, the values of the optimal compaction moisture decrease with the increase of the compaction effort, and the optimal compaction moisture of soils is generally considered to be approximately 85% of the value corresponding to saturation [18].

Vibrating compaction is considered one of the most modern methods of improving difficult foundation grounds, having a wide range of applicability. The compaction effect will be the greater the smaller the bonding forces between the particles and the more different the particle masses. That is why this technology is used especially in non-cohesive soils where the bonding forces between the particles are very small, but also in the case of inhomogeneous fillings, not being applicable to clayey soils.

In the case of the vibratory compaction process, a number of technological factors are known to be taken into account, namely:

- characteristics of the compaction equipment (mass per drum, drum width, frequency and amplitude of drum vibrations);
- soil characteristics (initial density, granularity, grain shape, moisture);
- working procedures (number of passes, thickness of the layer to be compacted, working frequency, speed of movement of the compactor).

Soil type has a significant influence on compaction characteristics. In general, cohesive soils show a high resistance to compaction, and non-cohesive soils can undergo slight compaction. The effort or energy of compaction is closely related to the type of technological equipment and the parameters of the working regime used in the compaction of the terrain. It was found that as the compaction effort increases, the compaction quality is better.

The equipment used for soil compaction can be classified into the following categories: static compactors, dynamic or impact compactors, vibrating compactors, etc. They have different types of working bodies: smooth or profiled rollers, tire train.

The thickness of the layer to be compacted is inversely proportional to the degree of compaction. For a given compaction energy, the efficiency of the compaction process will be lower for a thick layer compared to that obtained for a thinner layer. This aspect can be explained by the fact that, for the layer with a large thickness, the energy consumption per unit weight is reduced.

The number of passes of the compactor rollers increases the density of the soil, bearing in mind that determining the number of passes for a given type of equipment and soil at the optimum compaction moisture is essential for compaction efficiency.

The contact pressure depends on the weight of the equipment and the contact area. In the case of pneumatic rollers, the inflation pressure of the tires influences the additional contact pressure. A high contact pressure leads to an increase in the dry density and a decrease in the optimum compaction moisture of soils.

The speed of compaction depends on the type of equipment and the technology chosen for compaction, being generally limited to 5 km/h. The higher the compaction speed, the duration of the compaction process is significantly reduced. At a high compaction speed, there is a possibility that the time for the appearance of deformations is insufficient, and it is necessary to increase the number of passes for effective compaction. The lower the travel speed of the compactor, the more vibrations are produced at a given point and the fewer passes.

It should be noted that, depending on the type of terrain, the working technology can be static (that is, the machine does not use vibrations in the operating mode) or with vibration (in which case the machine can work with a single vibrating roller or with both, depending on its constructive variant). Typically, eccentric mass or eccentric shaft vibrators are used which generate different types of vibrations.

This information must be taken into account when developing dynamic models of interaction between the machine and the terrain, with the help of which to simulate the dynamic behavior of the vibratory roller-terrain with an impact on the evaluation of the performance of the compaction process, by identifying the final degree of compaction.

2. Automating the control and ensuring the quality of the compaction process through monitoring and digitization

2.1. Examples of good practice at international level

Common test methods used in situ to control and verify the quality of foundation base or backfill materials, which directly provide information on strength or modulus of elasticity, and which provide significant time savings in obtaining test results are presented in Figure 2.2.

Fig. 2.2 Common devices for in situ measurements of soil properties with: light weight deflectometer, dynamic cone penetrometer, Clegg hammer, test plate

Currently, there are numerous systems available internationally for the acquisition, measurement and processing of vibration signals, used as mobile laboratories for in situ testing of the quality of the works performed. Some such examples are illustrated in Figure 2.3 [25].

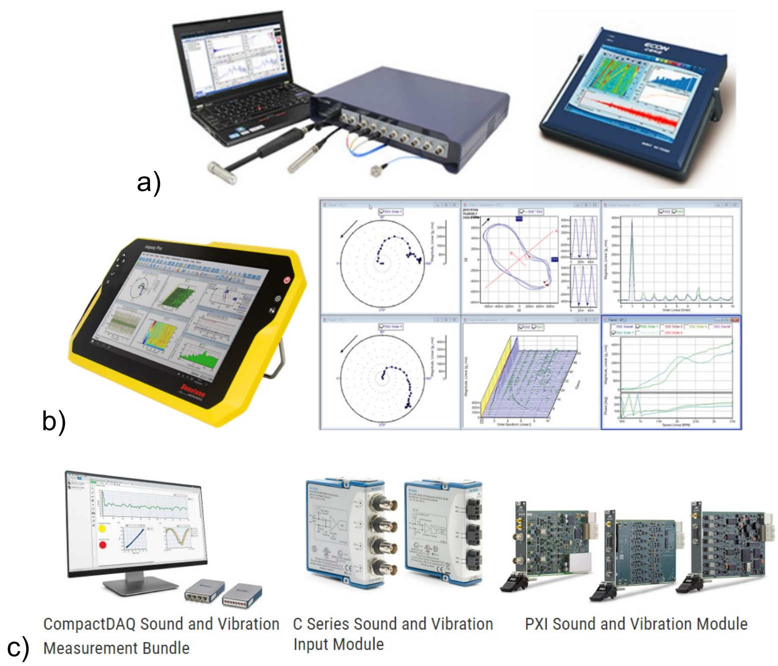


Fig. 2.3 High-performance systems for acquisition, measurement and processing of vibration signals:
a) Econ MI generația 7 /Dynamic Signal Analyzer Module [26]; b) impaq Pro Portable Vibration Analyzer [27]; c) PC-Based Sound and Vibration Devices / PXI Sound and Vibration Module USB 4431 [28]

The European Community initiated over 30 years ago the implementation of continuous compaction measurement and control (CCC) methods, so today modern vibratory compactors are equipped with continuous monitoring and control systems of parameters with significant influence on process performance compaction by vibration of the land. Three such 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:

$$\begin{cases} CMV = C_0 \cdot \frac{A_{2\omega}}{A_{\omega}} \\ CMV = \left(\frac{A_{0,5\omega}+A_{1,5\omega}+A_{2,5\omega}+A_{3\omega}}{A_{2,5\omega}+A_{3\omega}}\right) \cdot 100 \end{cases}, \quad (2.1)$$

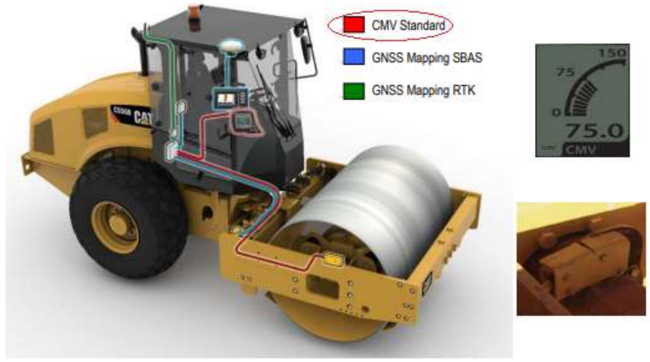


Fig. 2.4 Implementation of CMV technology [29]

By knowing the spectral composition of the acceleration signal of the vibratory roller in its movement in the vertical direction, the state 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 (Fig. 2.5).

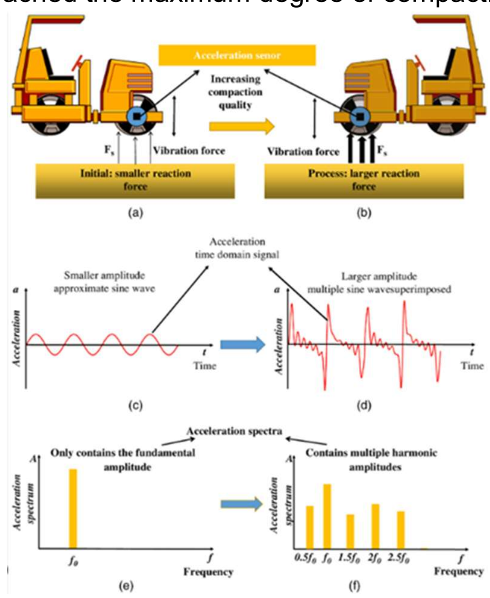


Fig. 2.5. The spectral composition of the vibration roller acceleration signal [30]

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 [33] 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* with calculation relation given in 2.2), *OMV* (*oscillometer value*) or *CCV* (*continuous compaction value*).

$$RMV = 100\frac{A_{0,5\omega}}{A_{\omega}} \tag{2.2}$$

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

- the variation of the energy transferred to the ground during the passes of the vibratory compactor, by evaluating the *OMEGA* parameter [Nm];
- the variation of the dynamic modulus of elasticity of the terrain during the passage over the layers, by monitoring the parameter E_{vib} [MN/m^2], according to Figure 2.8.

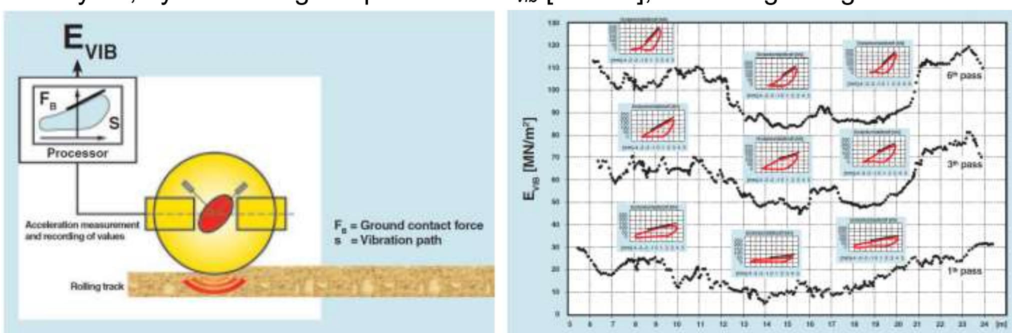


Fig. 2.8. E_{vib} parameter monitoring [34,35]

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, etc. In the case of compactors of the new generation from the BOMAG company (Fig. 2.9), they are equipped with a system called VarioRoller, later developed as VarioControl, which have the role of changing the direction of the dynamic force of the roller (Fig. 2.10) according to the characteristics of the compacted layer, directly related to the rigidity obtained after each pass of the machine.

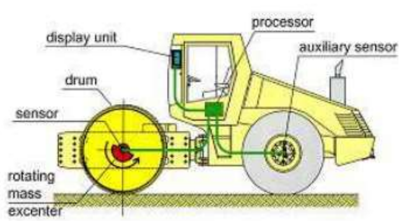


Fig. 2.9. Equipping with control systems for the compaction process [36]

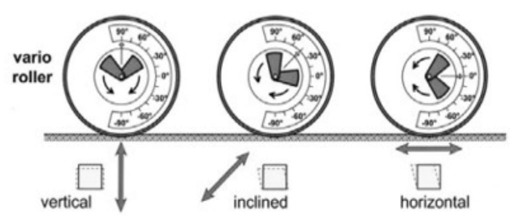


Fig. 2.10. Changing the direction of action of the dynamic force of the roller [36]

CCC – ACE - a technology that incorporates a new concept by which the variation of ground stiffness is monitored during the movement of the compactor on the terrain subjected to vibration compaction, by monitoring the parameter k_b [MN/m] (on Ammann/Case machines). The calculation relationship for estimating k_b is:

$$k_b = \omega^2\left[(m + m_0) + \frac{(m_0 e k_{vario})cos\varphi}{A_{(z)}}\right]. \tag{2.4}$$

MDP (Machine drive power) – a new technology for evaluating the degree of compaction of a layer, patented by CAT and implemented on Caterpillar B-Series compactors (Fig. 2.11). 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 [37]. Thus, this method directly measures the stiffness of the ground.

$$MDP = P_g - Wv\left(sin\alpha + \frac{A'}{g}\right) - (mv + b). \tag{2.5}$$

Fig. 2.11. Implementation of MDP technology [38]

Following a critical analysis of the previously presented aspects, it follows that five levels of acceptability are distinguished (table 2.3), used in the specialized literature [40] 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 2.3 Acceptability levels according to the degree of accuracy of the models for the evaluation of the vibratory compaction process [40]

No	Acceptability level description		Measured parameter	Aplication		Acuracy	Model
				S	MA		
1	Empirical models based on frequency response analysis of roller vibration		Harmonics index (*CMV*, *RMV*, *CCV*)	X	X	Low	N/A
	Empirical models based on frequency response analysis of roller oscillations		Harmonics index (*CCC*)	-	X	Low	N/A
2	Empirical energy models based on rolling resistance force response		Energy index (*MDP*)	X	-	Low	Dynamic / static
3	Static simplified models	Models for half-space Models with discrete elements: Kelvin-Voigt, Maxwell, Zener, Burgers etc.	Rigidity, modul, rolling force (E_{vib}, K_s)	X -	X X	Medium	Dynamic
4	Dynamic models		Module, rolling force (*VCV*)	X	-	Good	Dynamic
5	Dynamic models with artificial intelligence		Module estimation, density estimation (M_{NN}, r_{ODMS})	- X	X X	Excellent	Dynamic

Notation: S – soil; MA – asphalt mixture.

Summarizing, it can be seen that the factors that influence the compaction effect of soils and asphalt mixtures are divided into internal and external factors. Thus, the internal factors include, mainly, the characteristics of the materials and the strength of the base layer, and the external factors are represented by the compaction parameters of the working regime, the compaction energy, the construction of the working tool of the roller, the compaction mode (static or dynamic) and compaction technology (by taking into account the speed of the compactor, the number of passes, etc.) [25].

2.2. Digitization of Romanian industry in the context of Industry 4.0

In the field of construction, especially in the construction of roads and highways, there are regional specialization niches and potential niches to explore, as stipulated in the 2021-2027 Regional Smart Specialization Strategy (a project currently being implemented in our country) and digitalization is desired processes in this field of activity. By extrapolation, it is possible to move to a later stage, in which there is the possibility of integrating the IT system of each manufacturer of construction materials into a common digital platform, to which all the factors (designers, builders, beneficiaries and suppliers) involved are connected in a project with large volumes and working spaces, ensuring access to the necessary information and carrying out the transfer of this information in order to effectively fulfill the construction objective.

The current global and European state of digitization of construction activities and processes is perceived in developed countries through the increasingly widespread use of technologies and equipment equipped with intelligent systems, sensors, transducers, memory chips and links with GPS-type systems (Fig. 2.15), thus allowing the transfer of data, their processing and display in large-scale projects to be transposed into dedicated digital technological platforms with a restricted information circuit (intranet).

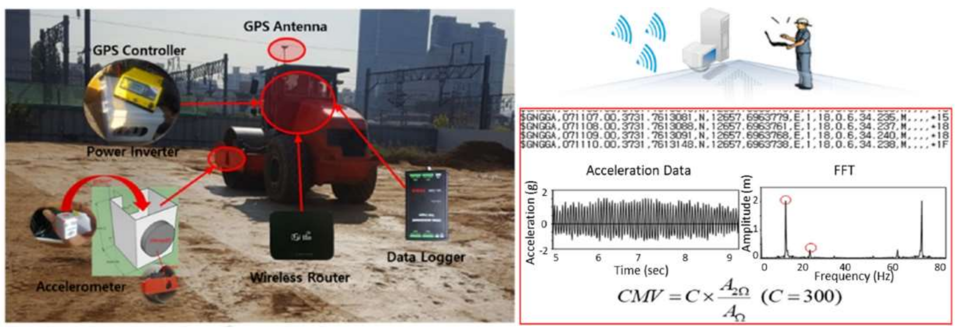


Fig. 2.15 Example of smart technology integration on vibratory compactors [41]

In our country too, there are steps to implement this concept of digitization of industry 4.0, in this sense an example with applicability in the field of road works is presented. Thus, in the procedure developed by ICECON S.A. called "Digitalization of processing and commissioning technologies of construction materials for road works", the performance requirements imposed to achieve the previously mentioned objective are highlighted [42]. Creating a consortium in the form of a digital platform to which all participants involved in the execution of a large-scale work (such as the construction of a highway) have access is a good option to put into practice. Another example (fig. 2.18) could be the monitoring of work with vibratory compactors during the execution of large-scale works, for the construction of special objectives (airport runways, highways, special foundations, etc.).

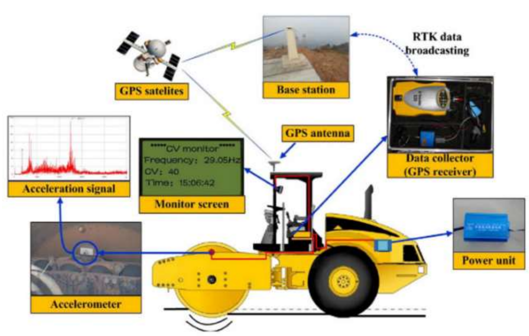


Fig. 2.18 Monitoring the working parameters of a vibratory compactor [44]

A new concept was first developed and applied in the USA in the early 2000s called Building Information Modeling (BIM). BIM symbolizes construction innovation based on the combination of technology, process and implementation with the aim of promoting the widespread use of digitization, simulation and process optimization through digital design, construction and operation in the virtual environment (using computer systems). For example, applying the principles of the BIM concept, Figure 2.19 illustrates the collaboration of the factors directly involved in the execution of a highway.

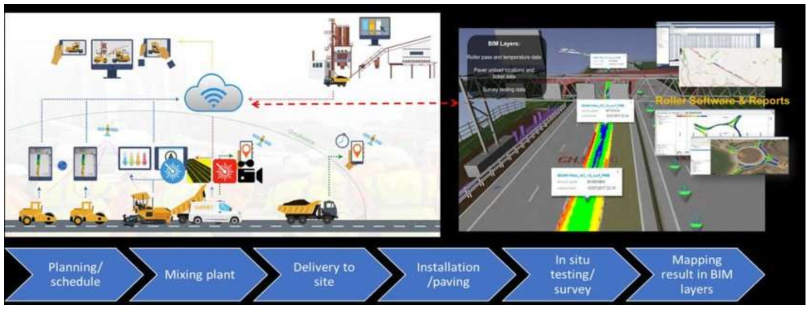


Fig. 2.19. Automatic data collection and compliance monitoring during the construction process of a highway [47]

3. Methods for analyzing the compaction process through laboratory and "in situ" investigations of soils used for road foundations

3.1. Evaluation of the geotechnical parameters of compaction soils

The most common tests performed in the laboratory to determine the various characteristics necessary to characterize the compaction are: oedometric sample; cyclic triaxial test; the Proctor test. The tests carried out in situ consist of: determining the static mode of linear deformation of the earth; determination of land settlement after a single pass of the compactor; experimental determination of the thickness of the layer to be compacted.

3.2. "In situ" tests for evaluating the parameters of the soil to be compacted

3.2.1. Identification parameters of the roller-terrain system

The width of the contact area of the compactor roller with the ground, according to the standard C 29-85, also depends on the degree of compaction D_i (defined in STAS 9850-89) determined by the Proctor test. For example, for the width b^* of the imprint of the vibrating roller of the CV 4 compactor (with D_r = 160 cm), in the case of Bucharest clay (weakly cohesive soil), the results [102]:

b^* = 24 ... 25 cm for loose soil, with D = 0,6; b^* = 12 ... 13 cm for compacted soil, with D = 0,86.

and technological ratio: b^*/D_r = 0,2 ... 0,21 for D = 0,6 and b^*/D_r= 0,1 ... 0,11 for D = 0,86.

For the vibrating roller of the VV 170 compactor (with roller diameter D_r = 160 cm), in the case of dusty clayey sand with unevenness index U_n = 67, the widths resulted [102]:

b^* = 25 ... 28 cm for loose soil, with D = 0,65; b^* = 11 ... 16 cm for compacted soil, with D = 0,8.

and technological ratio: b^*/D_r =0,16 ... 0,175 for D =0,65 and b^*/D_r =0,07 ... 0,1 for D =0,8.

It is noted that in both cases the values fall within the range indicated by the stipulations of the normative C 29-85.

3.2.2. Time of soil compaction and effective consolidation effort

The full compaction of the terrain (at the calculated maximum effort) is achieved when a sufficiently long time is required (called the time required to obtain a primary consolidation of

100%), corresponding to the significant decrease of the pressure in its pores. In all practical cases, the soil stress time when the machine passes over the layer is shorter than the primary consolidation time $t_p = t_{100}$, which means that the soil is consolidated with a fraction of the effective effort. The value of this fraction is determined, according to C 29-85 (point 2.14), based on the primary consolidation time (integral compaction) obtained by the method of semi-logarithmic representation (Casagrande) presented in STAS 8942/1-89 (point 6.4).

3.2.3. . Experimental tests to determine the modulus of elasticity E, G and the critical damping of the terrain

These parameters can be determined by laboratory and in situ tests according to technical guide P125-84. Following the experiments, in the case of compacting the Bucharest clay with the CV 4 compactor, the values $\delta = 1.02$ and $\zeta = 0.163$, respectively, were obtained for the determined average deformation $\varepsilon_a = 1.9 \cdot 10^{-2}$ cm/cm conditions of a degree of soil saturation of 60%). Knowing the values of G_d and ζ allows the determination of the dynamic amplification coefficient Ψ, used to determine the loading load on the roller, based on C 29-85 (point 2.6.). The ensemble of these experimentally determined parameters can generally be the basis of simulation models of soil behavior in the compaction process and, respectively, simulation models of the dynamic effects that occur during machine-terrain interaction, an aspect pursued with interest in this thesis. It can be concluded that in the compaction process, the soils show a limit (upper and lower) cyclic strength, and the compaction process is effective only if the stress falls between the two limits.

3.2.4. Systematization of experimental data for establishing the soil model in the compaction process

The evaluation of the set of geotechnical parameters that describe and characterize the site to be compacted is carried out in accordance with the requirements of C 29-85 which specify the performance of the following experimental tests [25, 54]:

a) ***laboratory tests:*** oedometric test (STAS 8942/3-90), cyclic triaxial test (P 125-84, Annex B), Proctor test (STAS 9850-89). These laboratory geotechnical tests help to determine the following parameters: the time of complete compaction of the terrain (C 29-85 point 2.14.), the oedometric modulus of deformation, the drawing of the stress-strain curve and the time variation of the pore pressure, the optimal compaction moisture and maximum dry weight or maximum dry density, degree of compaction, Proctor curve;
b) ***in situ tests***: determination of the static modulus of linear deformation of soils (by calculation, based on the oedometric modulus according to STAS 3300/2-85, point 3.4.5, or by direct measurement in situ, through the plate loading test according to STAS 8942/3), terrain settlement measurement following a single pass of the technological compaction equipment, experimental evaluation of the layer thickness (according to C 29-85 point 2.6 applying the procedure described in Annex 2.2., point 2).

Thus, based on all the phenomenological observations and the results of the primary data highlighted following the geotechnical determinations in the laboratory and in situ carried out by the specialists of the Geotechnical Laboratory and Foundations from INCERC Bucharest and the specialists in vibration measurements from the Research Institute for Equipment and Technologies in Construction – ICECON S.A. conclusions were synthesized that highlight specific dependencies and legalities between the characteristic parameters of the foundation terrains and the technical and technological ones of the compaction equipment viewed from the aspect of technological conditions. More precisely, it is concluded the need ***to correlate the operational performance of the compactor equipment with the characteristic parameters of the terrain to be compacted, taking into account the compaction technology chosen for practice***.

The centralization of all the information resulting from phenomenological observations creates the premises for the development of models for simulating the behavior of the terrain in the compaction process, valid until the phase of experimenting with the characteristic parameters of the terrain made at a given time, depending on the number of passes, based on some laws (established analytically and/or experimentally) between the $E_{st,}$ ρ_d, w_i, D_i parameter.

In conclusion, the statement can be made that, based on the real data of the geotechnical characteristics of the terrain, obtained through experimental determinations in the laboratory and in situ, the following models can be developed in the thesis:

a) *theoretical model for the study of soil behavior in the compaction process*, with its characteristic parameters that have predictable evolutions dependent on:
   - the initial state of the terrain, defined by the initial characteristic parameters;
   - roller-terrain contact, through the characteristic geometric parameters of the roller;
   - the roller load of the technological compaction equipment, by its static weight (when compacting without vibrations) and the amplitude and frequency of the dynamic force generated by the vibration generator (when dynamic compaction).

b) *rheological models for simulating the evolution of terrain settlement in the compaction process, highlighting the elastic, viscous and plastic components*;

c) *rheological models with different degrees of complexity for the simulation of technological equipment – terrain interaction in the compaction process* defined by [6]:
   - the action of the machine on the terrain is materialized by the value of the degree of compaction achieved at a given moment in the compaction process;
   - the action of the terrain on the machine is materialized by the value reached at a given moment in the compaction process of the stiffness coefficient of the terrain *k*;
   - the compaction technology correlates the imposed quality of compaction, the efficiency of using the machine in order to perform the imposed technological task and the global economic efficiency of the compaction technological process.

4. Experimental "in situ" evaluation of the static and dynamic compaction process

4.1. Experimental determinations to identify the evolution of the degree of soil compaction

In the case of the theoretical model for simulating the behavior of the terrain (MTC), the experiments and practical investigations carried out with the logistical support provided by ICECON S.A. Bucharest were carried out under real working conditions, within the modernization works of the DN 2 national road (Bucharest-Urziceni), the Movilița work point (km 39+200) and consisted of: monitoring the settlement achieved in the compaction process through determinations level topometric and geotechnical; checks of the characteristic parameters and the working regime of the compactor; verification of the applied work technology. Within the Geotechnical Laboratory and Foundations of INCERC and ICECON, the geotechnical samples were analyzed on the soil samples taken from the field by correlation with topometric level measurements, at different stages of the compaction process.

The location of the working section (with a length of 50 m) and the location of the measuring points (noted F...I, Ref.1), on the construction site with the working point Movilita, are indicated in the diagram in Figure 4.1.

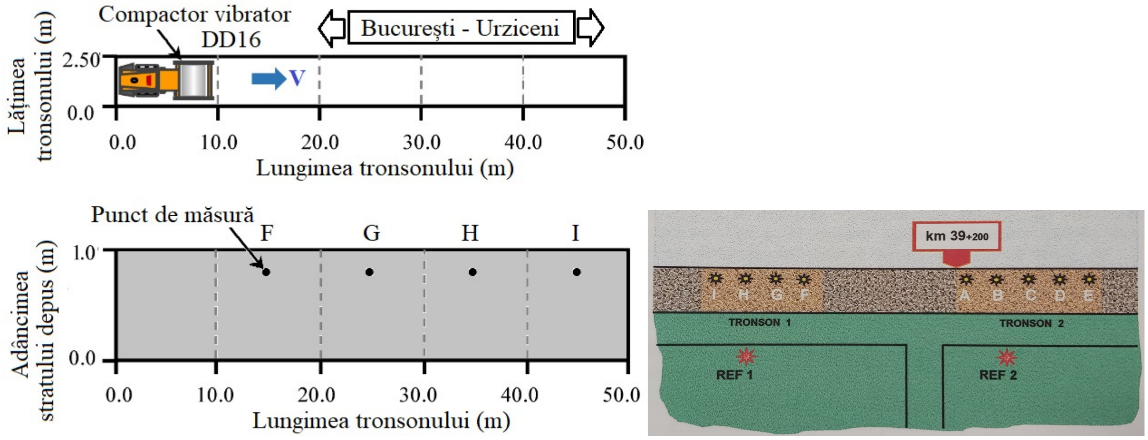


Fig. 4.1. The location of the compacted section and the measurement points and the way of carrying out the tests on the experimental ground polygon built on the construction site on DN 2, Movilita work point, km 39+200

The measurement points F...I represent different terrain variants because, although the nature of the soil was the same and the characteristic geotechnical parameters ρ_{dmax} and t_c identical in value, the initial state geotechnical parameters ρ_{di}, E_{sti} and w_i had different values. All these parameters defined 4 different variants of the same terrain, subjected to compaction. Additionally, the initial thickness of the deposited soil layer, perceived as an element of the applied technology, also defines a different initial state for the compaction process.

Investigations A: Attempts to establish the nature and physico-mechanical characteristics of the terrain begin with the description of the evidence for the general characterization of the terrain and the initial state of the soil. It is specified that the soil used for filling was brought from the Movilita borrow pit (located on DN 2, at km 43+500), and the soil samples for carrying out the checks were taken from the deposited layer, both for the laboratory of the official consultant of the work, as well as for the ICECON S.A. Bucharest laboratory.

Investigations B: The tests to follow the evolution of the compaction process begin with the verification of the characteristic parameters of the compactor and the verification of the working regime during compaction. When compacting the soil, a VV 170 compactor was used (intended especially for the compaction of non-cohesive soils, with a power of 98 kW), equipped with a smooth vibrating roller on the front and with normal tires on the rear. Since approx. 66% of the total weight of the machine (15710 daN) is distributed on the roller, it makes it possible to compact the terrain even in static conditions.

4.2. Experimental determinations to identify the behavior of the machine-soil system in the compaction process

The validation of the theoretical model of soil behavior (MTC) was done under the conditions of the operation of the compactor machine without vibration, based on the results of the experimental investigations carried out in real working conditions, on the construction site of the national road DN 2 Bucharest - Urziceni. Additionally, to test the model in vibration regime, experimental investigations were carried out in the soil channel within ICECON S.A. Bucharest, specially designed for the identical simulation of real working conditions. In this situation, the compaction was carried out with the compactor type ABG – DD16 which has two smooth, vibrating rollers. The experimental tests provided for verifying the parameters of the vibratory working regime of the compactor consisted in the acquisition of signals of time variation of the vibration amplitude by integrating the primary acceleration signals acquired with acceleration transducers located directly on the jacket of the vibrating roller (fig. 4.4), in the direction vertical, in the area of its contact with the ground and on the upper chassis of the machine, for both rollers.

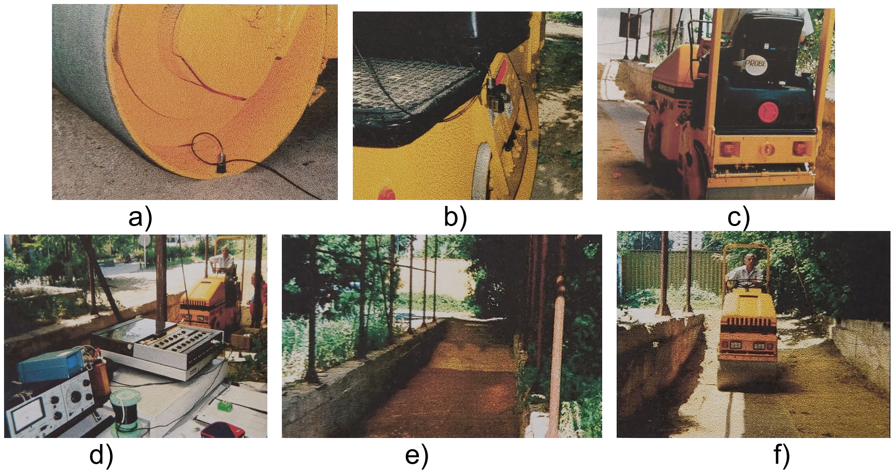


Fig. 4.4 Images from the experiment [102]:
a) mounting the acceleration transducer on the front roller casing, in contact with the ground; b) mounting the acceleration transducer in the upper part of the rear chassis; c) the test machine – the ABG DD 16 compactor; d) the system of measuring devices for determining the parameters of the vibration regime of the sample compactor; e) the earth channel with the layer of loose earth deposited; f) ABG DD 16 compactor on runway 1.

The experimental plan that was the basis of the in situ investigations is synthetically described in the diagram in figure 4.5.

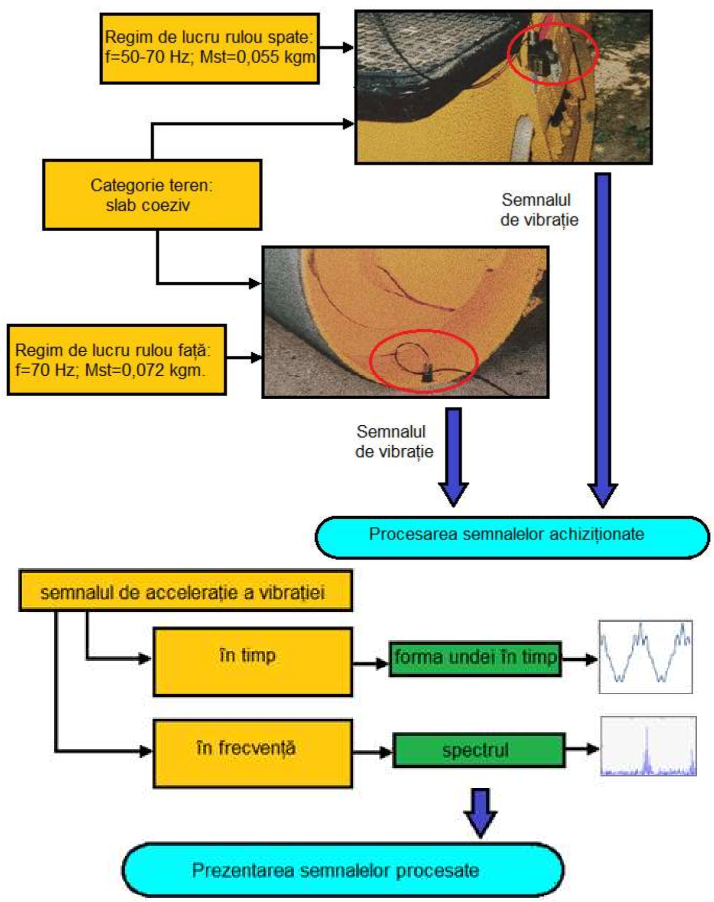


Fig. 4.5 The experiment plan

The verified vibration operating regimes were defined by:

a) operation of the front drum vibrator at nominal and maximum speeds;
b) simultaneous operation of the vibrators of both drums, at nominal and maximum speeds.

For each work situation, the frequency analysis of the recorded acceleration and displacement signals allowed to know the amplitudes and frequencies of the vibrations transmitted to the ground. Finally, the parameters of the vibration regime were verified, the compactor being able to operate with a correct vibration regime, maintaining the frequency and amplitude at stable values over time. The characteristics of the soil deposited for compaction in the earth channel were also verified by laboratory geotechnical tests. The length of the compacted track in the earth channel was L = 12 m, and the working speed of the machine was v_l = 1.44 km/h. Based on the dynamic response analysis method, several samples were made on which the vibration level was determined by recording the signal and then its spectral decomposition. Thus, every two passes, the signal was recorded. The results are presented in Figures 4.6 - 4.11, in the form of diagrams of the roll vibration amplitude spectra.

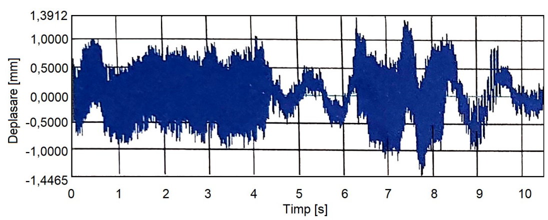


Fig. 4. The time variation of the displacement of the front roller, in the vertical direction, upon contact with the ground (Testing conditions: weakly cohesive soil channel – Bucharest, ABG DD 16 compactor, $m_o r$ = 0,0720 kgm, f = 70 Hz, passes **12**)

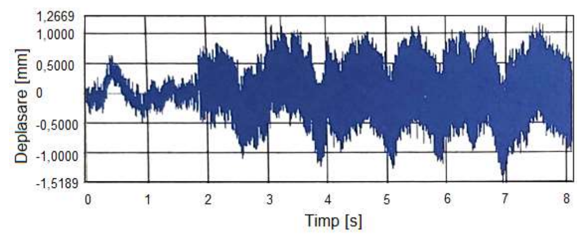


Fig. 4.7 The time variation of the displacement of the front roller, in the vertical direction, upon contact with the ground (Testing conditions: weakly cohesive soil channel – Bucharest, ABG DD 16 compactor, $m_o r$ = 0,0720 kgm, f = 70 Hz, passes **14**)

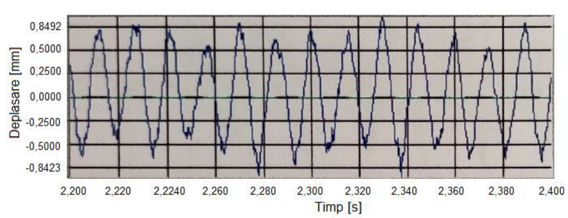


Fig.4.8 Detail from passes equivalent to 12

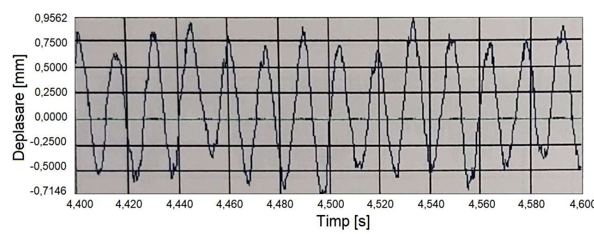


Fig. 4.9 Detail from passes equivalent to 14

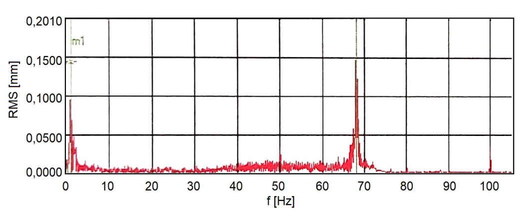


Fig. 4.10 Spectrum of the front roller displacement signal, in the vertical direction, at ground contact (marker m_1: f_1 = 0,95 Hz; A_1 = 0,0990 mm; marker m_2; f_2 = 68,12 Hz; A_2 = 0,1500 mm)

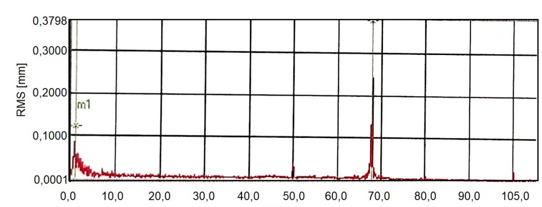


Fig. 4.11 Spectrum of the front roller displacement signal, in the vertical direction, at ground contact (marker m_1: f_1 = 0,95 Hz; A_1 = 0,1237 mm; marker m_2; f_2 = 67,84 Hz; A_2 = 0,3798 mm)

From the comparative analysis of the 2 sets of records and analysis it is concluded:

- the decrease in the spectral amplitude from passes 12 to passes 14 of the compactor;
- the invariance of the dominant spectral frequencies (f_1 =0.95 Hz, f_2 = 67-68 Hz, f_3 = 50 Hz);

- spectral equalization on the analysis domain between the two passes of the compactor.

The values of the dominant frequencies are identified as follows:

- 0.95 Hz corresponds to the machine's own frequency;
- 50 Hz is the natural frequency of the terrain when reaching the maximum degree of compaction;
- 67 - 68 Hz corresponds to the vibration working regime of the machine.

The experimental investigations highlighted the very fast compaction effect achieved by the compactor even when it operated with a single roller in vibration mode.

Based on the values obtained after each pass, ratios can be calculated between the amplitude at the fundamental pulsation and the amplitudes corresponding to the other pulsations (of order 2, 3, etc.) depending on the criterion that is intended to be applied in the evaluation of the performance of the compaction process (by identifying the indices CMV and RMV). These aspects were detailed in chapter 2 (relations 2.1 and 2.2) of this doctoral thesis. Depending on the number of passes of the machine on the same layer, there is an increase in the ratio between the amplitude of the 2nd order harmonic and the fundamental one, which highlights the accentuation of the terrain settlement phenomenon. The spectral analysis performed on the acquired signals corresponding to the movement of the compactor roller allows the provision of useful data for the design of a special system for determining the degree of compaction in real time with direct implications on the optimization of the technological and operational parameters of the machine. The results of the experimental geotechnical determinations that were made by taking samples from the soil, starting from the initial state, during the compaction process (after predetermined number of passes) and until the compaction is completed, are centralized in table 4.7.

Table 4.7 Experimental data from compaction with ABG DD – 16, with front vibratory roller in vibration mode. Runway no. 1 [102]

Passes no	Compaction regime	b_F^* [cm]	Share terrain [cm]	*Δh* [cm]	w_{med} [%]	ρ_d [g/cm^3]	*f* [Hz]	*v* [km/h]
0.....3	statically	16	9,93	0	9,8	1,465	70	1,44
3	vibrations F	-	-	-		1,82		
6	vibrations F	8	-	-		1,85		
7	vibrations F	7	10,88	0,95		1,873		
8	vibrations F	6	11,40	1,47		1,9		
9	vibrations F	5,5	11,42	1,49		1,953		

The experimental investigations highlighted the very fast compaction effect achieved by the compactor even when it operated with a single roller in vibration mode. One explanation would be the nature of the terrain (very weakly cohesive soil) and its low initial moisture (w_i = 11.2 % instead of w_{opt} = 19.8 %), which prevented stable geotechnical sampling until the initial 3 passes were performed static after which the required consistency was obtained (having the disadvantage of the moisture drop to 9.8%) but with the increase of the initial degree of compaction to the value of 85%, well above the value normally found in natural soils.

4.3. Interparametric correlations determined based on laboratory and experimental in situ investigations to characterize compaction performance

4.3.1 The law of dependence between static longitudinal modulus and density in dry state

Centralizarea legilor de variație $E_{st} = f(\rho_d)$, obținute pentru cele patru tipuri de pământuri slab coezive (testate, iar punctele de măsură notate cu F, G, H, I) este dată în Tabelul 4.8.

Tabelul 4.8 Centralizarea legilor de variație $E_{st} = f(\rho_d)$

Puncte de măsură	Grosimi straturi, [cm]	Legi de variație aproximative	Abaterea medie pătratică
F, G, H, I	24,5 - 29,5	E_{sti} =1000,6ρ_{di}^2 - 2230,8ρ_{di} + 1235,1	R^2 = 0,9927
		E_{sti} = 3,579 $\rho_{di}^{8,6369}$	R^2 = 0,9852
		E_{sti} = 814,25ρ_{di} - 1056,9	R^2 = 0,9842
		E_{sti} = 0,0224 $e^{5,6855\rho_{di}}$	R^2 = 0,9802
		E_{sti} = 1229,6$ln(\rho_{di})$ – 327,5	R^2 = 0,9787

A comparative analysis shows that the law that approximates with the smallest error the dependence between the two parameters (E_{st} and ρ) is the 2 degree polynomial type (fig. 4.12).

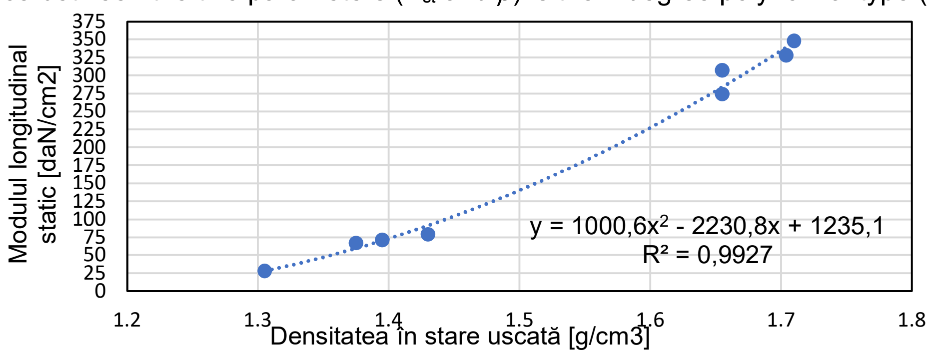


Fig.4.12. Dependence of the static modulus of linear deformation as a function of the density in the dry state, for weakly cohesive soil (experiments under static conditions)

So, for the implementation in an algorithm of a calculation program based on these parameters (in particular, for a certain phase of the technological process or in an evolutionary way, during the compaction process, after a certain number of passes), the $E_{sti} = f(\rho_d)$ law valid for weakly cohesive soils, can have a convenient analytical expression as follows:

$$E_{sti} = 1000[\rho_{di}^2 - p_c\rho_{di} + (p_c - 1)] \text{ [daN/cm}^2\text{]}, \quad (4.1)$$

where: E_{sti} - the static modulus of linear deformation of the soil, in [daN/cm^2];

ρ_{di} - the dry density of the earth, achieved at a given time, in [g/cm^3];

p_c – technological factor of compaction depending on the characteristics of the compactor and the terrain, calculated with the following relation:

$$p_c = \frac{Q}{0{,}18D_r^2} \text{ [daN/cm}^2\text{]}. \quad (4.3)$$

where: Q is the weight of the roller [daN]; D_r – roller diameter [cm].

Practically, for the VV 170 compactor system (operating in static mode) and the foundation soil consisting of weakly cohesive soil - Giurgiu clay, the value resulted: $\boldsymbol{p_c}$**=2.22**. The result is the proposed $E_{st} = f(\rho_d)$ law:

$$E_{sti} = 1000(\rho_{di}^2 - 2{,}22\rho_{di} + 1{,}22) \text{ [daN/cm}^2\text{]}. \quad (4.4)$$

The comparative representation of the two approximate polynomial laws, the first determined on the basis of experimental data (Table 4.8), and the second being proposed by the author of this thesis in the form of relation (4.1) is given in figure 4.13.

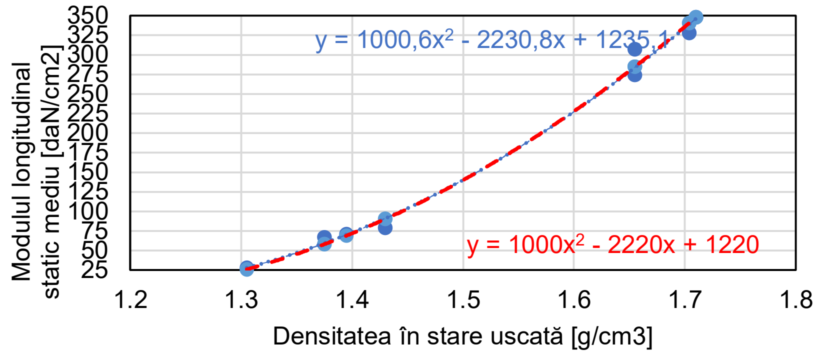


Fig. 4.13 Comparative reprezentation of $E_{st} = f(\rho_d)$ law:
experimental (blue color) vs analytical – proposed (red color)

In conclusion, the results obtained and represented in figure 4.13 show a ***very high degree of similarity of the shape of the curve and validate the polynomial law proposed by the author of the thesis in relation (4.4)***. If the experimental results obtained for each of the four measurement points are considered, then the results centralized in Table 4.9.

Table 4.9 Centralization of variation laws E_{st} = ρ_i for each type of soil analyzed

Measuring point	Layer thickness	Inițial density	Inițial moisture	The law of approximate variation
F	26,5 cm	0,745ρ_{dmax}	0,60w_{opt}	E_{st} = 714,28 ρ_i - 903,71
G	24,5 cm	0,797ρ_{dmax}	0,85w_{opt}	E_{st} = 833,33 ρ_i - 1091,33
H	28 cm	0,785ρ_{dmax}	0,66w_{opt}	E_{st} = 833,33 ρ_i – 1079.25
I	29,5 cm	0,817ρ_{dmax}	1,04w_{opt}	E_{st} = 1000 ρ_i - 1352

4.3.2 The law of the dependence of the density in the dry state and the average moisture

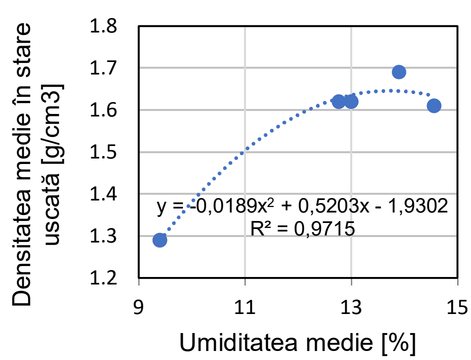


Fig.4.15 The law of variation of density in the dry state as a function of soil moisture with layer thickness h_c = 26,4 cm
(F point measurements, Annex 3)

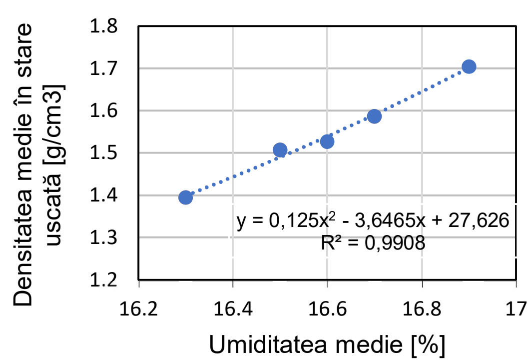


Fig.4.16 The law of variation of density in the dry state as a function of soil moisture with layer thickness h_c = 24,5 cm
(G point measurements, Annex 3)

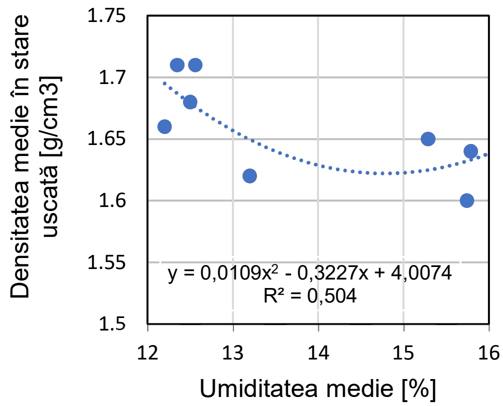


Fig.4.17 The law of variation of density in the dry state as a function of soil moisture with layer thickness h_c = 28 cm (H point measurements, Annex 3)

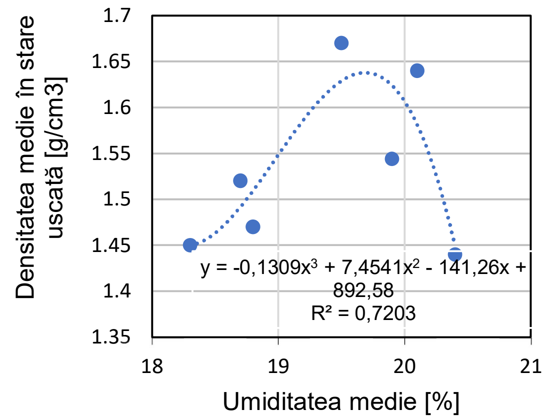


Fig.4.18 The law of variation of density in the dry state as a function of soil moisture with layer thickness h_c = 29,5 cm (I point measurements, Annex 3)

Table 4.10 Centralization of variation laws $\rho_d = f(w)$

Measuring point	Layer thickness	The law of approximate variation	The root mean square deviation
F	26,5 cm	ρ_d = -0,0189w^2+0,5203w-1,9302	R^2 = 0,9715
G	24,5 cm	ρ_d = 0,125w^2-3,6465w+27,626	R^2 = 0,9908
H	28 cm	ρ_d = 0,0109w^2-0,3227w+4,0074	R^2 = 0,5040
I	29,5 cm	ρ_d= -0,1309w^3+7,4541w^2-141,26w+892,58	R^2 = 0,7203

Based on the experimental data from the measuring point F (with w = 11 ... 13.6%), the author proposes to use the following relation for calculating the density in the dry state:

$$\rho_d = \rho_{dmax} - \sqrt{(\rho_{dmax} - \rho_{di})^2 - k_\rho\left(w_{opt} - w_i\right)\rho_{dmax}^2 \frac{\Delta h}{D_r}} \text{ [g/cm}^3\text{]}, \quad (4.5)$$

where: k_ρ - index depending on the number of passes of the compactor; k_ρ= 0,7 for the first 4 passes; k_ρ= 0,6 for the 5 – 12 passes; Δh – the cumulative settlement of the terrain, which has been achieved at a given time, in [cm]; D_r – roller diameter, in [cm].

4.3.3 The law of dependence between the width of the contact area, degree of compaction,settlement, number of passes

$$b^* = 0{,}667 D_r \sqrt{(1 - D_i)^2 - k_\rho \frac{\Delta h}{D_r}} \text{ [cm]}, \quad (4.6)$$

where the settlement Δh and the diameter D_r of the compactor roller are in [cm] and the degree of initial compaction D_i is dimensionless.

During the experiments carried out in the earth channel at ICECON S.A. Bucharest, in the case of compaction with vibrations, the lengths of the contact spots of the front vibrating roller were measured, and the data in Table 4.7 were the basis for identifying the law of variation in figures 4.19 and 4.20.

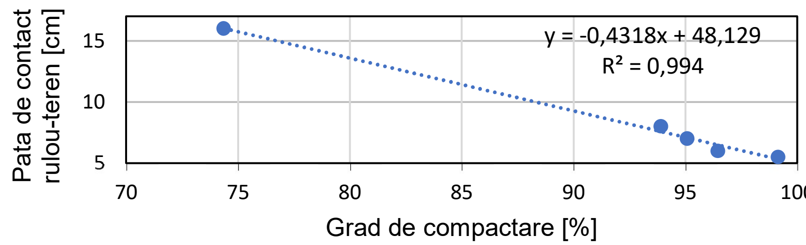


Fig. 4.19 The law of variation of the contact patch according to the degree of soil compaction (experimental measurements in the earth channel)

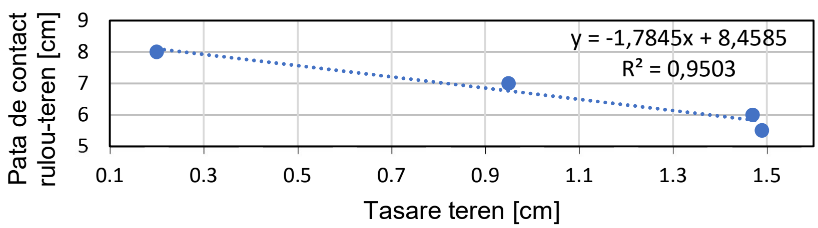


Fig. 4.20 The law of variation of the contact patch according to terrain settlement (experimental measurements in the earth channel)

It is noted that the variation trend of the change in the length of the contact patch between the vibratory roller and the ground is linear, intensely decreasing, with a high degree of approximation (>95%), an aspect that facilitates the calculation algorithm attached to a model for the behavior of a certain type of soil under the action of the applied technological load. The evaluation of the performance of the compaction process can also be done by expressing the dependence between the dimensions of the contact spot and the degree of soil compaction. In fig. 4.21 approximation laws are exemplified (centralized in table 4.11), with mean square error >98%.

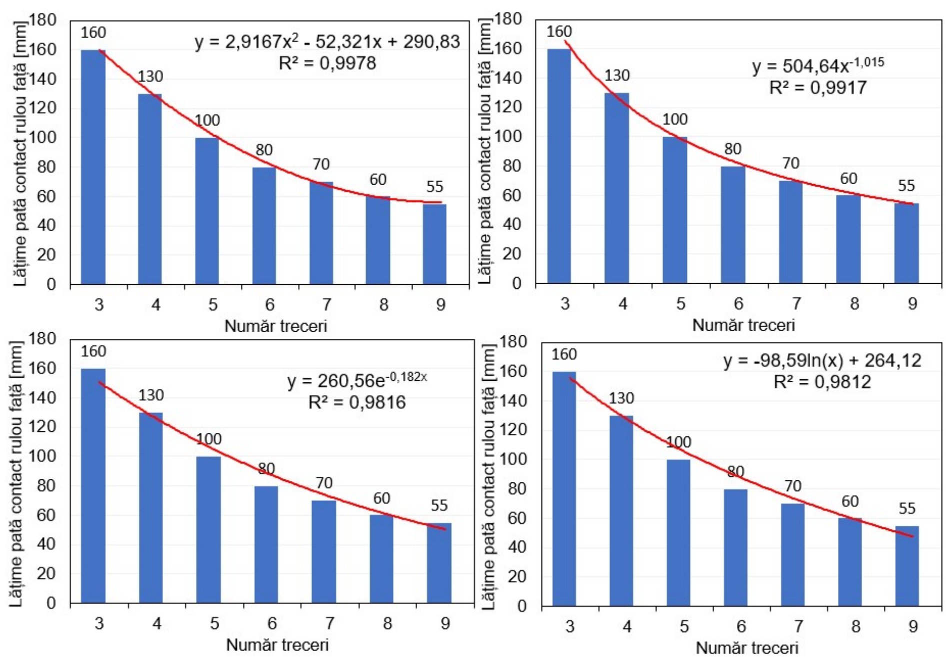


Fig. 4.21 Approximation law of the variation of the width of the contact patch on the front vibrating roller of the ABG – DD16 compactor, when compacting the terrain on runway no.1 (after the first 3 passes made in static working mode with the machine)

Table 4.11 Centralization of variation laws $b^* = f(N)$

Measuring point	The law of approximate variation	The root mean square deviation
The earth channel. Runway 1	$b^* = 2{,}9167N^2 - 52{,}321N + 290{,}83$	$R^2 = 0{,}9978$
	$b^* = 504{,}64N^{-1{,}015}$	$R^2 = 0{,}9917$
	$b^* = 260{,}56\text{x}10^{-0{,}182N}$	$R^2 = 0{,}9816$
	$b^* = -98{,}59\ln(N)+264{,}12$	$R^2 = 0{,}9812$

4.3.4 The law of the dependence of the specific pressure in the terrain and settlement

$$\frac{\Delta h}{h_c} = 1000(25{,}1p - 33{,}3), \tag{4.7}$$

where does it result from

$$\sigma(N) = 4 \cdot 10^{-5}\frac{\Delta h(N)}{h_c} + 1{,}32 \text{ [daN/cm}^2\text{]}, \tag{4.8}$$

where: Δh is the settlement achieved by the machine during the load stress t_c of the terrain during a pass; h_c – the thickness of the compacted layer.

To create a simulation scenario of the compaction process, it is much easier to calculate an expression of the dependence of a parameter in time, so that the analytical expression for approximating the function $\Delta h/h_c$–t_c (corresponding to the variation of settlement) will also be indicated specific $\Delta h/h_c$ during the stress time under load t_c), which has the form (see fig. 3.9):

$$\frac{\Delta h}{h_c} = 0{,}0049Ln(t_c) + 0{,}0529. \tag{4.9}$$

4.3.5 The law of the dependence of the stiffness and natural frequency of the soil on the density in the dry state

$$k(N) = \frac{1{,}13E_{st}(N)\sqrt{Bb^*(N)}}{1-\vartheta^2}. \tag{4.10}$$

$$f_0(N) = \frac{1}{4h_c}\sqrt{\frac{G(N)}{\rho(N)}}. \tag{4.11}$$

4.3.6 The law of the dependence of settlement on the number of passes of the compactor established for each type of soil analyzed

During the compaction process, after the machine passes (without the use of vibrations), measurements were made regarding the current and cumulative settlement of the analyzed land, corresponding to the 4 measurement points (F - I). The obtained results were the basis for the identification of the approximation laws for the variation of settlements by the number of passes of the compactor (figures 4.22-4.25). Centralization of variation laws of cumulative settlement $\Delta h_c = \Delta h_c(N)$ are given in Table 4.12.

Table 4.12 Centralization of variation laws $\Delta h_c = \Delta h_c(N)$

Measuring point	Layer thickness	Inițial density	Inițial moisture	The law of approximate variation
F	26,5 cm	$0{,}745\rho_{dmax}$	$0{,}60w_{opt}$	$\Delta h_c = -0{,}0205N^2 + 0{,}4265N + 1{,}0739$
G	24,5 cm	$0{,}797\rho_{dmax}$	$0{,}85w_{opt}$	$\Delta h_c = -0{,}0128N^2 + 0{,}2736N + 0{,}3409$
H	28 cm	$0{,}785\rho_{dmax}$	$0{,}66w_{opt}$	$\Delta h_c = -0{,}0164N^2 + 0{,}4197N + 0{,}038$
I	29,5 cm	$0{,}817\rho_{dmax}$	$1{,}04w_{opt}$	$\Delta h_c = -0{,}0013N^2 + 0{,}2005N - 0{,}074$

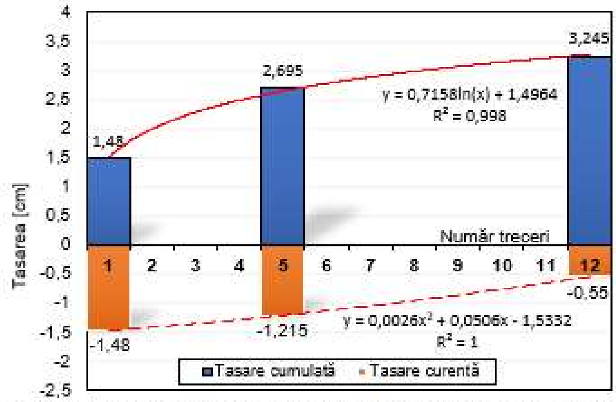


Fig. 4.22 Variația tasării curente și cumulate pentru trecerile compactorului (măsurători în punctul F, Anexa 3)

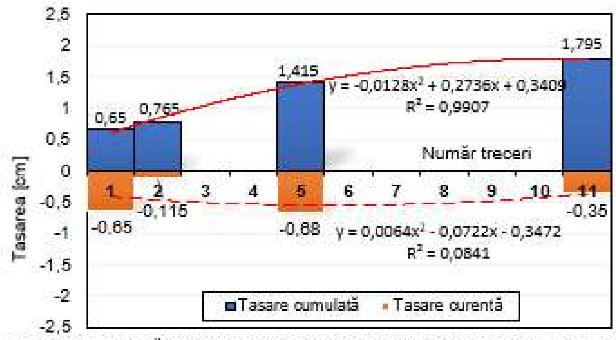


Fig. 4.23 Variația tasării curente și cumulate pentru trecerile compactorului (măsurători în punctul G, Anexa 3)

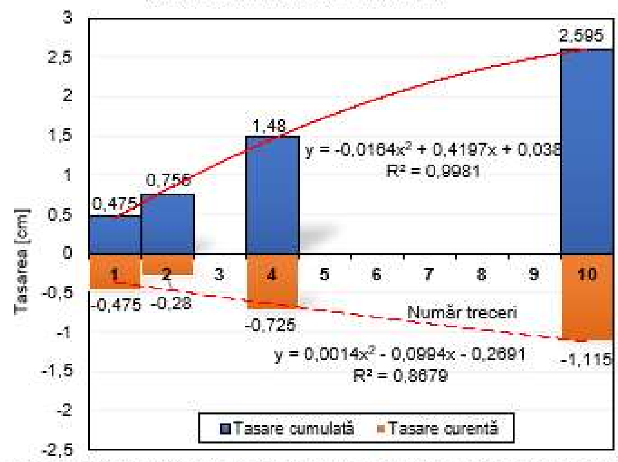


Fig. 4.24 Variația tasării curente și cumulate pentru trecerile compactorului (măsurători în punctul H, Anexa 3)

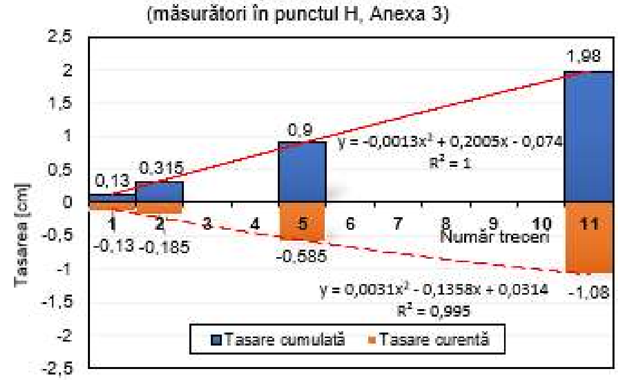


Fig. 4.25 Variația tasării curente și cumulate pentru trecerile compactorului (măsurători în punctul I, Anexa 3)

4.3.7. The law of the dependence of the degree of compaction on the number of passes of the compactor established for each type of soil analyzed. In establishing the laws (Fig. 4.26–4.29, Tab. 4.13) the evolution of the degree of compaction of a material was taken into account, which is assimilated due to mathematically with the graph of a logarithmic function that admits a horizontal asymptote corresponding to the compressibility limit of the soil.

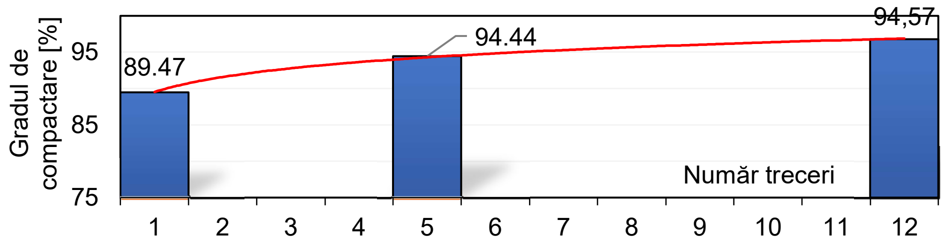


Fig. 4.26 The variation of the degree of compaction according to the passes of the compactor, corresponding measurements at point F, for terrain with initial degree of compaction D_i=74.5%

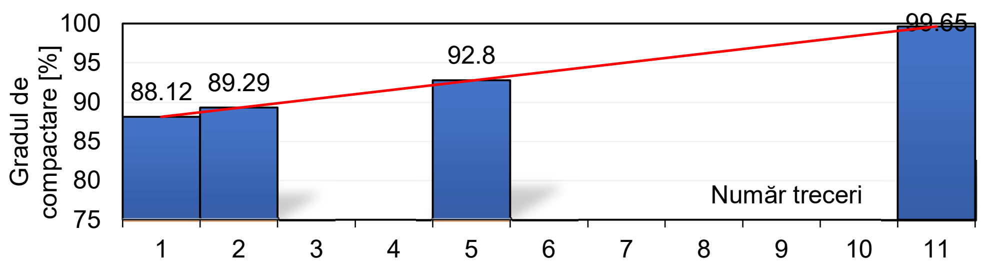


Fig. 4.27 The variation of the degree of compaction according to the passes of the compactor, corresponding measurements at point G, for terrain with initial degree of compaction D_i=79,7%

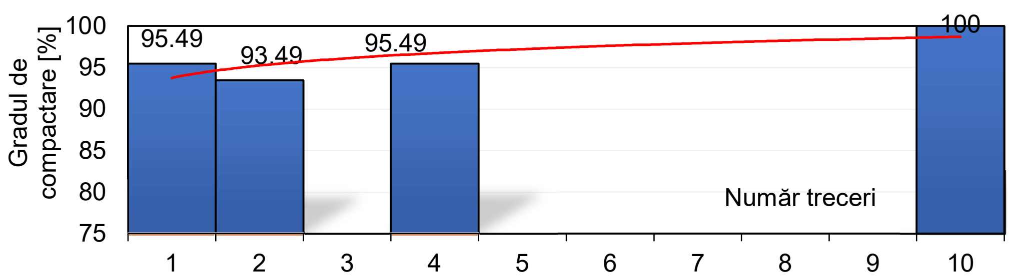


Fig. 4.28 The variation of the degree of compaction according to the passes of the compactor, corresponding measurements at point H, for terrain with initial degree of compaction D_i=78,5 %

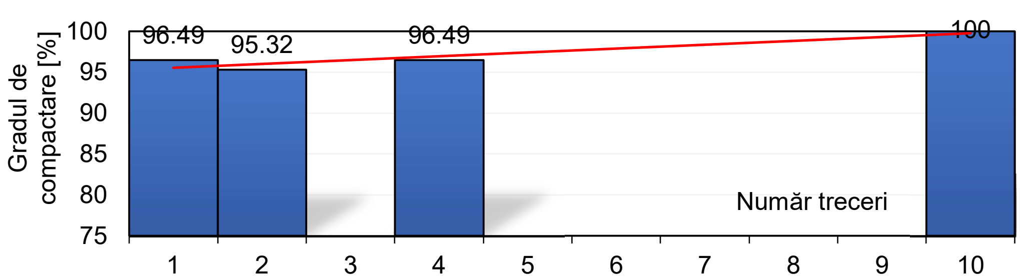


Fig. 4.29 The variation of the degree of compaction according to the passes of the compactor, corresponding measurements at point I, for terrain with initial degree of compaction D_i=81,7%

Table 4.13 Centralization of variation laws $D_i = D_i(N)$

Measuring point	Layer thickness	Inițial density	Inițial moisture	The law of approximate variation
F	$0{,}57h_{opt}$	$0{,}745\rho_{dmax}$	$0{,}59w_{opt}$	- for N = 1…12: $D_i(N) = 2{,}9599\ln(N) + 89{,}524$; $R^2 = 0{,}9987$ or $D_i(N) = 0{,}6273N + 89{,}80$; $R^2 = 0{,}8753$.
G	$0{,}83h_{opt}$	$0{,}797\rho_{dmax}$	$0{,}85w_{opt}$	- for N = 1…11: $D_i(N) = 1{,}1525N + 86{,}991$; $R^2 = 1$.
H	$0{,}86h_{opt}$	$0{,}785\rho_{dmax}$	$0{,}66w_{opt}$	- for N = 1…10: $D_i(N) = 2{,}152\ln(N) + 93{,}76$; $R^2 = 0{,}5907$ or $D_i(N) = 0{,}5859N + 93{,}835$; $R^2 = 0{,}8846$.
I	$1{,}24h_{opt}$	$0{,}817\rho_{dmax}$	$1{,}04w_{opt}$	- for N = 1…10: $D_i(N) = 0{,}468N + 95{,}086$; $R^2 = 0{,}8667$.

Taking into account the fact that during the compaction process, it is recommended that the first 3 passes be carried out statically, and the following ones with the rollers in vibration mode (dynamic), the author of the doctoral thesis proposes a linear empirical relationship for calculating the predicted degree of compaction to be obtained, after each of the 3 passes, based on the parameters that characterize the initial state of the terrain (initial density in dry state ρ_i, maximum density in dry state of the terrain ρ_{max}, initial moisture w_i, optimal moisture of the terrain w_{opt}, number of N passes). The relation is of form:

$$D_i(N) = \left(2 - \frac{\rho_i}{\rho_{max}}\right) \cdot N + \alpha \cdot \frac{\rho_i}{\rho_{max}} \cdot \left(1 + 0.001 \cdot \frac{w_i}{w_{opt}}\right), \tag{4.13}$$

where α is a correction coefficient defined as follows:

$$\alpha = \begin{cases} 1.135 \ dacă \ 70\% \le D_i < 75\% \\ 1.0 \ dacă \ 75\% \le D_i < 80\% \\ 1.025 \ dacă \ 80\% \le D_i < 85\% \\ 1.1 \ dacă \ D_i \ge 85\%. \end{cases} \tag{4.14}$$

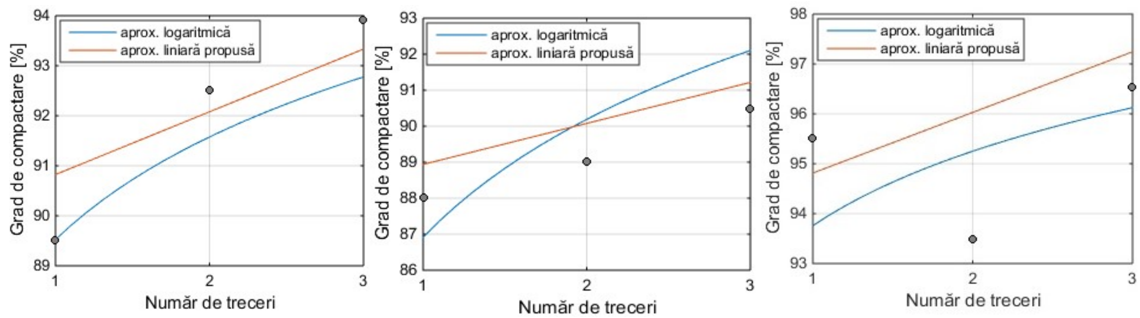
The validity of the relation (4.13) must also be correlated with the technological index of the machine im defined by the relation

$$i_m = \beta \frac{m_r}{BD_r} \text{ [kg/m}^2\text{]}, \tag{4.15}$$

where: m_r is the drum mass; B – roller width; D_r – roller diameter; β - coefficient of load amplification when the roller works with vibrations, which is calculated as the ratio between the dynamic force and the weight of the roller. In static working conditions with the compactor roller, this coefficient has a value equal to 1.

It is specified that the technological index of the VV 170 compactor has the value i_m = 0.27 kg/cm^2. Also, it must be specified that the initial moisture of the terrain must not exceed the optimal moisture resulting from the Proctor test, for the relation (4.13) to be valid.

Next, figure 4.30 shows the evolution of the degree of compaction for the first 3 static passes, in the case of the 3 measurement points (F, G, H) that meet the application conditions of the proposed relationship.



a) b) c)

Fig. 4.30 Comparison between approximation laws for the degree of compaction, for the first 3 static passes, corresponding to measurements from:
a) point F; b) point G; c) point H.

An overview of the performance of the compaction process obtained in the case of the 4 analyzed types of terrain, under working conditions with the VV 170 compactor (without vibrations) is presented in figure 4.31. It is observed that the value of the degree of compaction has a significant increase up to the 5th pass of the compactor, followed by a decrease in the intensity of the increase for the following passes.

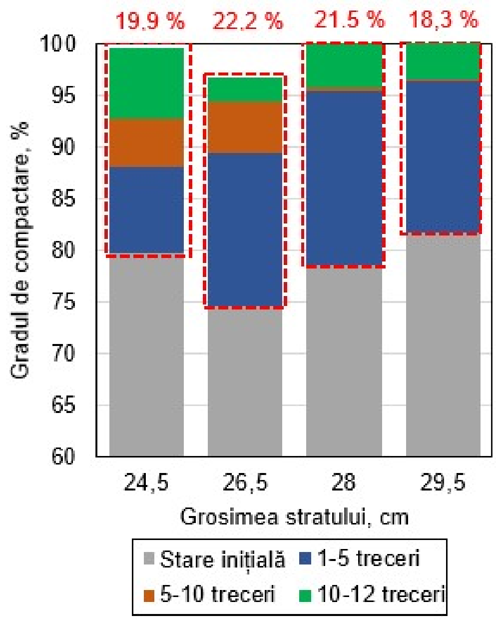


Fig. 4.31 The variation of the degree of compaction according to the initial condition of the terrain, the thickness of the layer and the number of passes of the compactor, corresponding to the measurements from points F, G, H, I

The previously described aspects show the different behaviors of the 4 types of terrain under the action of the same technological load transmitted by the roller, which highlights the complexity and specificity of the compaction process seen as a whole, making it difficult to accurately forecast the achievement of the required degree of compaction even if it is known a wide range of parameters that describe the initial state of the land.

4.4 Partial conclusions

The set of experimental tests performed and the systematization of the results (after their processing) were presented in a form that would allow the user to implement them in a computer calculation algorithm. Thus, all the legalities identified, proposed and centralized in this sub-chapter of this doctoral thesis are particularly useful for the development of a theoretical model of soil behavior (MTC) then integrated into a model to be the basis of the study of the compaction organ interaction (static or vibratory roller) – terrain, in compliance with the scope of existence of these laws (percentage of optimal moisture or maximum density in dry state, range of layer thicknesses, technological index of the compacting machine, number of passes, applied technology).

5. Rheological modeling and simulation of roller-terrain interaction

5.1 Working principles of inertial vibrators for increasing the efficiency of the compaction process

Actuations of the vibrating rollers of the compaction machines can be with a single vibrator or with two, the latter being the most widespread, ensuring the synchronous rotation of the eccentric masses. Regardless of their constructive variant, the generation of vibrations for the dynamic actuation of the compactor roller is the result of the development of a dynamic force(s) that has/have different directions depending on the positioning of the eccentric mass(es).

5.2.2. Mathematical modeling of terrain response to harmonic inertial dynamic excitation

The modeling of a vibration phenomenon based on the Voigt-Kelvin rheological schematization is based on a model composed of two elements, one elastic and the other viscous, connected in parallel, which is subjected to inertial dynamic excitations (Figure 5.4) in order to simulate the functional behavior of the vibrating technological equipment, as well as the effect of its action on the working environment. The kinematic excitation is $x(t)=A_0 sin\omega t$ and results in an energy transfer to the base (i.e. soil), thus producing a dynamic response from the ground quantifiable by evaluating the viscous force *Q(t).*

It is specified that the terrain will be modeled with viscoelastic elements, with their identical characteristics (fig. 5.4) for a certain state and a technological regime, making it possible to approach the simulation of compaction using a linear viscoelastic system.

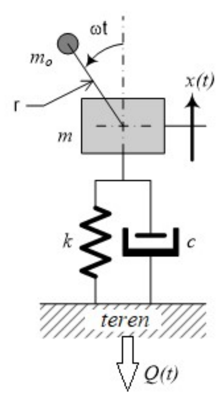


Fig. 5.4. Schematization of the Voigt-Kelvin rheological model with constant parameters

Next, in order to analyze the effect produced in the field by the action of the vibratory roller, the following clarifications will be made [76,77]:

a) inertial type excitation in rotational motion of mass m_0 with radius *r* and angular velocity ω, is generated by a harmonic force function of the form:

$$F(t) = m_0 r\omega^2 sin(\omega t)\,; \tag{5.2}$$

b) the response to the instantaneous displacement of the roller is of the form $x(t)=A sin\omega t$, and reaction force (response of the ground to the action of the roller) is $Q(t) = Q_0 sin\,(\omega t - \varphi)$;

c) the dynamic equilibrium differential equation has the following form:

$$m\ddot{x} + c\dot{x} + kx = m_0 r\omega^2 \sin\omega t, \tag{5.3}$$

where the reaction force can be expressed by the first-order equation: $Q(t) = c\dot{x} + kx$.

After introducing the usual notations $p^2 = \frac{k}{m+m_0}$, $\Omega = \frac{\omega}{p}$, $\zeta = \frac{c}{2(m_0+m)p}$, the amplitude of the dynamic force that directly and significantly influences the dynamic response of the model has the following calculation expressions

$$F_0 = m_0 r\omega^2 = m_0 r p^2 \Omega^2 = m_0 r \frac{k}{m+m_0}\Omega^2 = F_0^{st}\Omega^2 = kA_{st}, \tag{5.4}$$

where: A_{st} represents the amplitude at post-resonance: $A_{st} = m_0 r / (m_0+m)$;

F_0^{st} - the force corresponding to the elastic deformation with A_{st}: $F_0^{st} = m_0 rk / (m_0+m)$.

The terrain response force to the roller action has the calculation relationship:

$$Q_0 = F_0^{st}\Omega^2 \sqrt{\frac{1+4\Omega^2\zeta^2}{(1-\Omega^2)^2+4\Omega^2\zeta^2}}. \tag{5.5}$$

The dynamic transmissibility T of motion is defined as follows:

$$T = \frac{Q_0}{F_0^{st}\Omega^2} \tag{5.6}$$

or after replacing the parameters:

$$T = \sqrt{\frac{1+4\Omega^2\zeta^2}{(1-\Omega^2)^2+4\Omega^2\zeta^2}}. \tag{5.7}$$

The amplitude of the movement corresponding to the instantaneous displacement as a response of the system is:

$$A = \frac{\Omega^2 A_{st}}{\sqrt{(1-\Omega^2)^2+4\Omega^2\zeta^2}} \tag{5.8}$$

so $A = A(\Omega, \zeta)$ is a function expressed in relative pulsation Ω and damping fraction ζ.

Since the value of the stiffness of the compacted layer increases with each pass (until reaching the maximum value corresponding to the maximum degree of compaction, after which it remains constant in value) it can be said that this stiffness is dynamic.

5.2.3. Mathematical modeling of (variable stiffness) terrain response to harmonic inertial dynamic excitation

In this subsection, a dynamic model with varying stiffness is presented (Figure 5.5), so that for each pass of the vibratory roller on the same layer, a certain stiffness will be achieved, and after *n* passes, *n* values for the stiffnesses will be reached $k_1, k_2 \ldots\ldots k_n$.

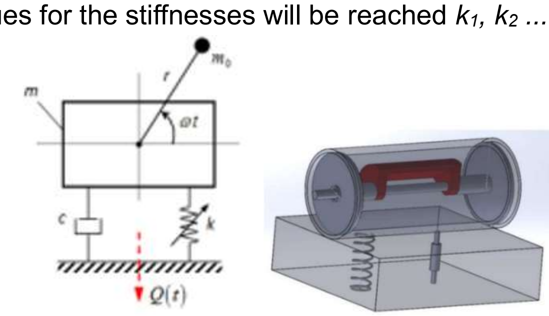


Fig. 5.5 Schematization of the Voigt-Kelvin rheological model with variable parameters

The dynamic response will be given in the form of the amplitude of the vibration displacement, denoted by A [67-69, 72]. Thus, for each model, the increasing influence of the stiffness on the parametric values will be observed.

The expression of the amplitude of the motion is of the form:

$$A^{V-K}(\Omega,\zeta) = \frac{m_o r}{m}\frac{\Omega^2}{\sqrt{(1-\Omega^2)^2 + 4\Omega^2\zeta^2}}. \quad (5.10)$$

The response force of the terrain to the action of the roller is of the form:

$$Q_0{}^{V-K}(\Omega,\zeta) = \frac{k\Omega^2 m_o r}{m}\sqrt{\frac{1+4\Omega^2\zeta^2}{(1-\Omega^2)^2 + 4\Omega^2\zeta^2}}. \quad (5.11)$$

The dynamic transmissibility is given by the formula:

$$T^{V-K}(\Omega,\zeta) = \sqrt{\frac{1+4\Omega^2\zeta^2}{(1-\Omega^2)^2 + 4\Omega^2\zeta^2}}. \quad (5.12)$$

By compaction, the pressure at the bottom of the soil through each layer increases with the number of strokes of the vibratory roller and reaches its maximum value when the soil has its maximum dry density [79]. The energy dissipated in the vibration compaction process can be calculated with the relation [73]:

$$W_d = \pi c \omega A^2 \quad (5.13)$$

or considering the relation (5.10)

$$A = m_0 r \omega^2 \frac{1}{\sqrt{(k-m\omega^2)^2 + c^2\omega^2}} \quad (5.14)$$

results:

$$W_d = \pi c (m_0 r)^2 \frac{\omega^5}{(k-m\omega^2)^2 + c^2\omega^2}. \quad (5.15)$$

In conclusion, it is found that the force transmitted to the ground depends on the static moment of the vibrator, the mass of the roller, the stiffness of the layer after compaction, the pulsation and the relative damping, while the transmissibility depends only on the stiffness and damping of the soil layer.

5.2.4. Numerical simulation of terrain response to harmonic inertial dynamic excitation

In the case of the topic addressed in this thesis, on the one hand, the functional behavior of a vibratory compactor is studied, and on the other hand, the transmissibility and amplitude of vibrations felt in weakly cohesive fill soils.

Among the known categories of soils, for the study of the dynamic behavior of elastic or elastoplastic soils under the action of vibrations transmitted in the compaction process, it is recommended to use the Voigt-Kelvin model [80] whose predominantly elastic characteristic lends itself very well to the simulation of the dynamic response of these terrains that are characterized by a reduced influence of natural viscosity in the overall stress-strain characteristic. It is considered a roller compactor in vibration mode, modeled as a vibrating system using the Voigt-Kelvin model, in which the ground stiffness has distinct values, and the pulsation of the source of vibration with values between ω = 0...500 rad/ s. The parameters represented by the viscous damping coefficient *c* and the damping fraction ζ will be assigned distinct values to model the real compaction process, since after each pass of the vibratory compactor intermediate states (*i*) of the settlement of the soil layers characterized by a change of their stiffness (until reaching the required degree of compaction, *D*[%]). In practice, each distinct value of the soil stiffness (k_i), obtained after the passage *i* of the vibratory compactor, corresponds to a certain value of the viscous damping coefficient (c_i), which indicates the response of the soil to the action of the disturbing force transmitted by the vibratory roller. It should be emphasized that between the two parameters there is a relationship of form interdependence $c = 2\zeta\sqrt{km}$, and the damping fraction must be limited by value $\zeta \leq 0{,}7$, thus resulting in the range of values with which the numerical simulation was performed in the case study presented in this doctoral thesis, namely: ζ = 0,16...0,7.

Two simulation scenarios were carried out, as follows:

a) scenario 1: the stiffness parameter k_i was varied with discrete values and the curves represented in figures 5.6 – 5.9 were obtained by numerical simulation with the variation of model-specific parameters (vibration amplitude *A*, force transmitted to the ground *Q* and transmissibility *T*), as and of the energy dissipated in the field, of the dynamic stiffness, of the critical damping fraction in relation to the excitation source pulsation ω, with both parameters *k* and *c*, with the pulsation ratio Ω;

b) scenario 2: the critical damping fraction ζ_i was varied with discrete values and the curves represented in figures 5.10 - 5.13 were obtained by numerical simulation.

In both simulation scenarios, 2 different cases of work regimes were considered:

– *case 1: fast working regime (with high frequency);*
– *case 2: slow working regime (with low frequency).*

Based on the input quantities centralized in Table 5.1 and the equation of motion of the roller-terrain system, an algorithm was implemented in the Matlab environment to evaluate the parameters of interest of the compaction process, as well as to highlight the mode of frequency variation or interparametric correlations [54].

Table 5.1. The identification data of the first simulation scenario in case 1

Initial terrain data
- soil category: filling soil, weakly cohesive - static elastic modulus: E_{st} = 139,4 daN/cm^2 - critical damping ratio: ζ=0,283 - initial compaction degree: D_i =0,8567
Initial vibratory drum data
-drum mass: *m*= 830 kg -static moment: $M_{st}=m_0r$=0.066 kgm -excentricity: *r* = 0,066 m -excentricity masses: m_0 = 1 kg -drum width: *B*=0.80 m -drum diameter: D_r=0.62 m -vibration frequency of working regime: *f* = 48 Hz -dynamic force: F_0= 6480 N -roller speed in working regime: V_{max}=1.44 km/h
Initial drum roller – terrain interaction data
- fast working mode: with high frequency vibration - type interaction modeling with Voigt-Kelvin model: k=2x10^6, 4x10^6, 6x10^6, 8x10^6 10x10^6 N/m and c=3x10^4 Ns/m

a)

b)

c)

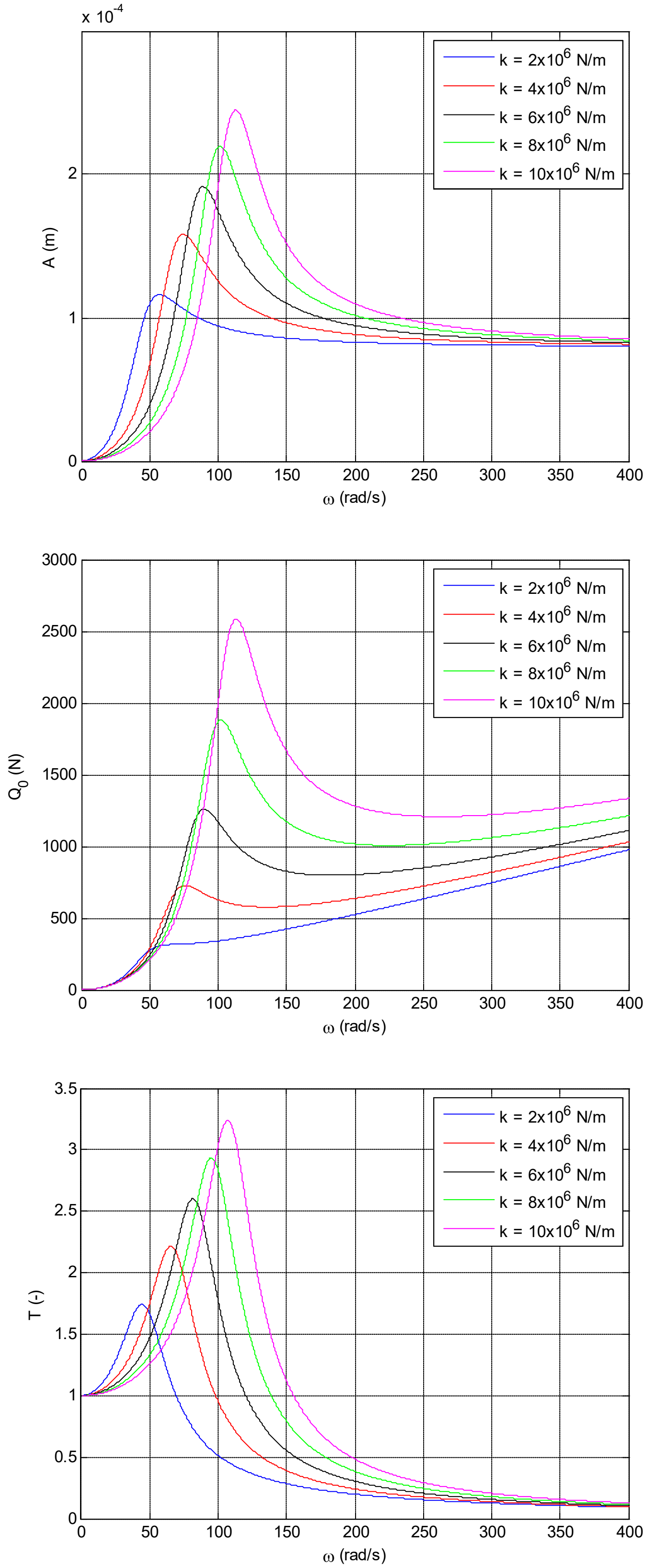


Fig. 5.6 The variation of vibration amplitude *A*, the force transmitted to the terrain Q_0 and the transmissibility *T* in relation to the pulsation of the exciting source.The first simulation scenario in case 1

The correlations of the three parameters, such as roller vibration amplitude, transmitted force, transmissibility, depending on the changes in ground stiffness and damping, at the working frequency (i.e. for ω = 301.5929 rad/s), are illustrated in the graphical representations in fig. 5.7.

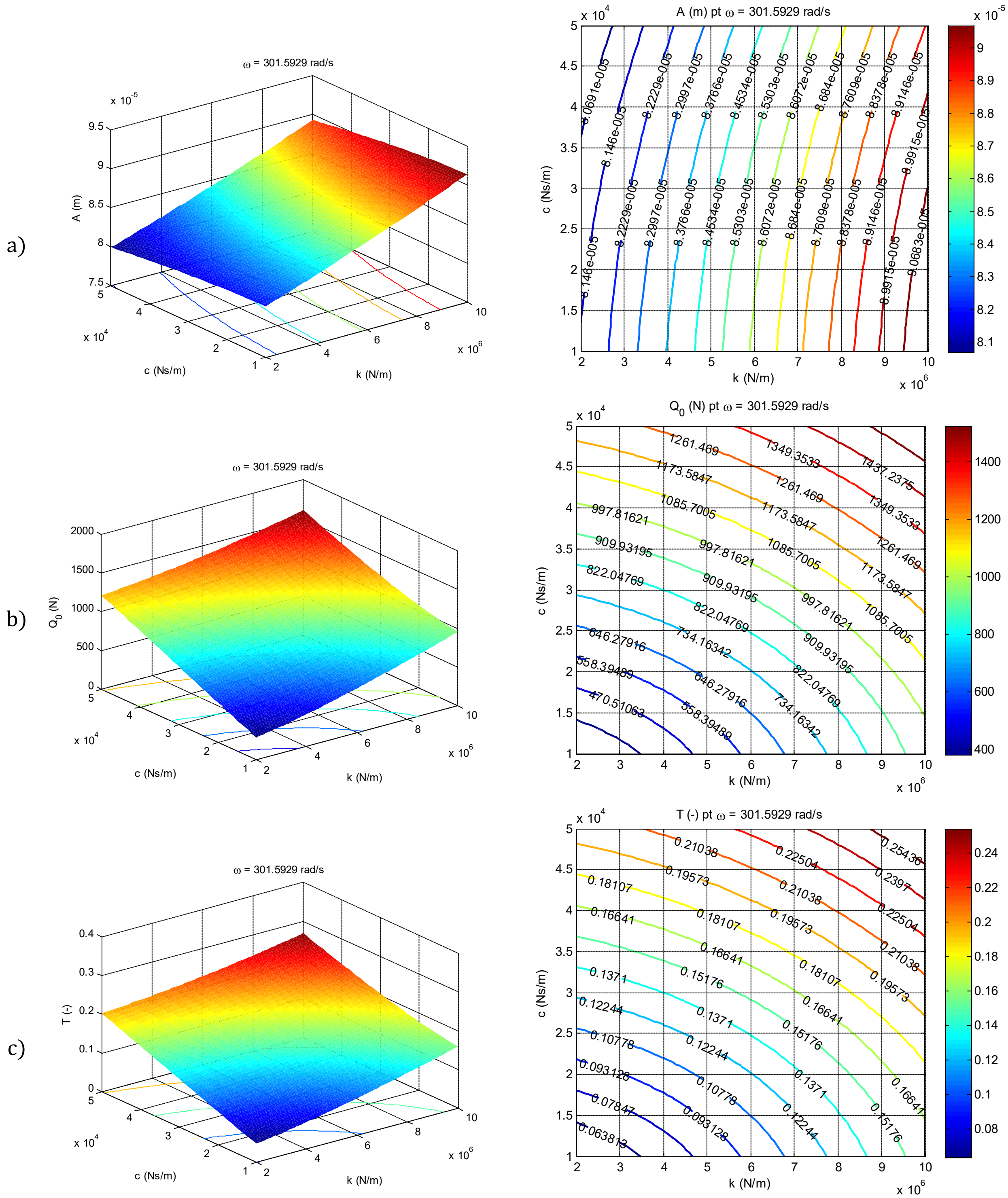


Fig. 5.7 The variation of vibration amplitude *A*, the force transmitted to the ground Q_0 and the transmissibility *T* in relation to the stiffness and damping of the terrain.
The first simulation scenario in case 1

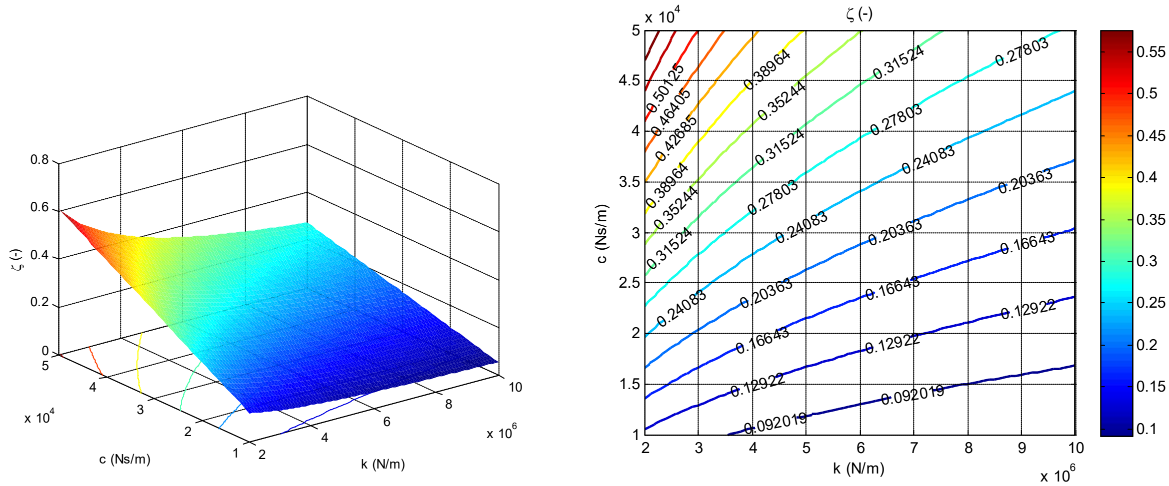
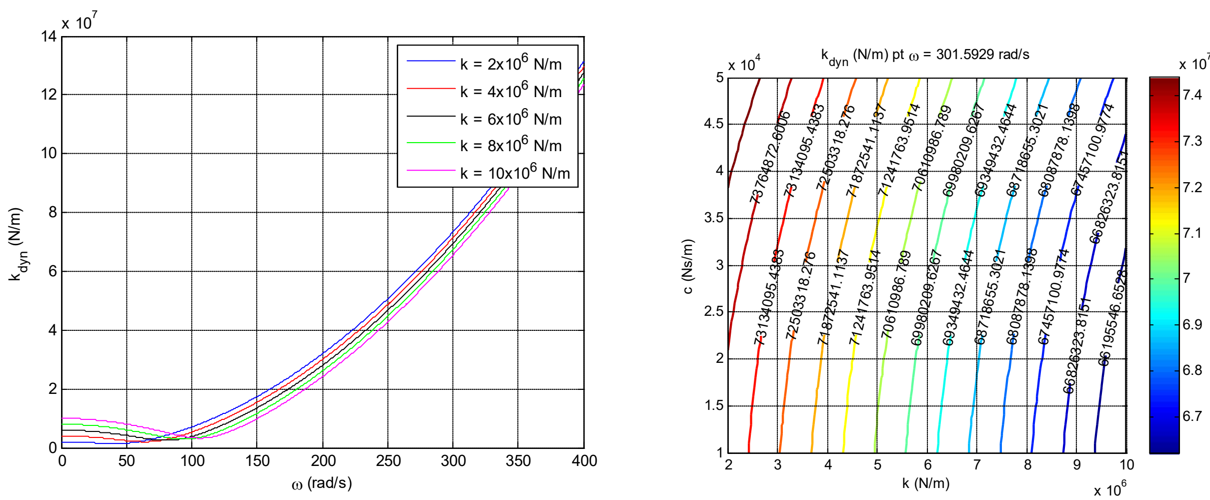


Fig. 5.8. Variation of critical damping fraction with respect to terrain stiffness and damping. The first simulation scenario in case 1

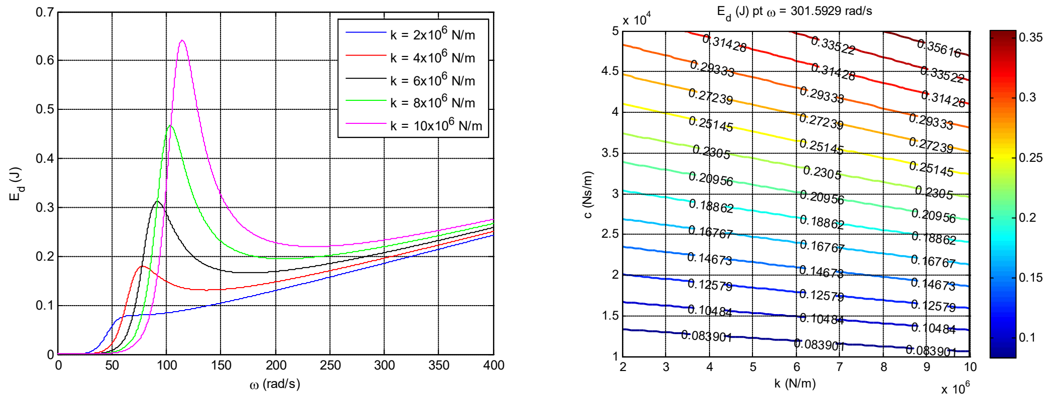


a) b)

Fig. 5.9 Variation of dynamic stiffness according to:

a) pulsation of the exciting source; b) the stiffness and damping of the terrain, for the working frequency.The first simulation scenario in case 1

It is observed that the difference between the stiffness k_0 and k_{din} is significantly greater when the vibratory roller machine works in the post-resonance regime, which is highlighted by the representations in figure 5.9. Thus, it can be observed that, for the discrete variation of the damping, the dynamic stiffness obtained at the angular velocity ω_1 close to that corresponding to the roller's own pulsation ω_n increases with the increase of the critical damping coefficient ζ. In contrast, in the post-resonance vibration operating regime region, i.e. for $\omega_2 \gg \omega_n$, the damping influence becomes negligible, but the dynamic stiffness increases significantly with the increase of ω_2 with respect to the resonance frequency. Based on the analysis of the dynamic behavior of a technological equipment of vibration compaction, it was observed that: the dynamic stiffness analysis performed according to the damping structural parameter, at the continuous variation of the excitation frequency, is an analysis method that provides relevant information for the evaluation of the behavior of the vibratory roller-terrain system, modeled as a dynamic linear viscoelastic system with one degree of freedom, with variable parameters.



a) b)

Fig. 5.10 The variation of energy dissipated in the terrain according to:
a) pulsation of the exciting source; b) the stiffness and damping of the terrain, for the working frequency.The first simulation scenario in case 1

Next, proceed similarly, for case 2 of the first simulation scenario which is defined in Table 5.2.

Table 5.2. The identification data of the first simulation scenario in case 2

Initial terrain data
- soil category: filling soil, weakly cohesive - static elastic modulus: E_{st} = 139,4 daN/cm^2 - critical damping ratio: ζ=0,283 - initial compaction degree: D_i =0,8567
Initial vibratory drum data
-drum mass: m= 830 kg -static moment: $M_{st}=m_0r$=0,187 kgm -excentricity: r = 0,187 m -excentricity masses:m_0 = 1 kg -drum width: B=0.80 m -drum diameter: D_r=0.62 m -vibration frequency of working regime: f = 25 Hz -dynamic force: F_0= 4680 N -roller speed in working regime: V_{max}=1.44 km/h
Initial drum roller – terrain interaction
- slow working regime: with low frequency vibrations - type interaction modeling with Voigt-Kelvin model: k=2x10^6, 4x10^6, 6x10^6, 8x10^6 10x10^6 N/m and c=3x10^4 Ns/m

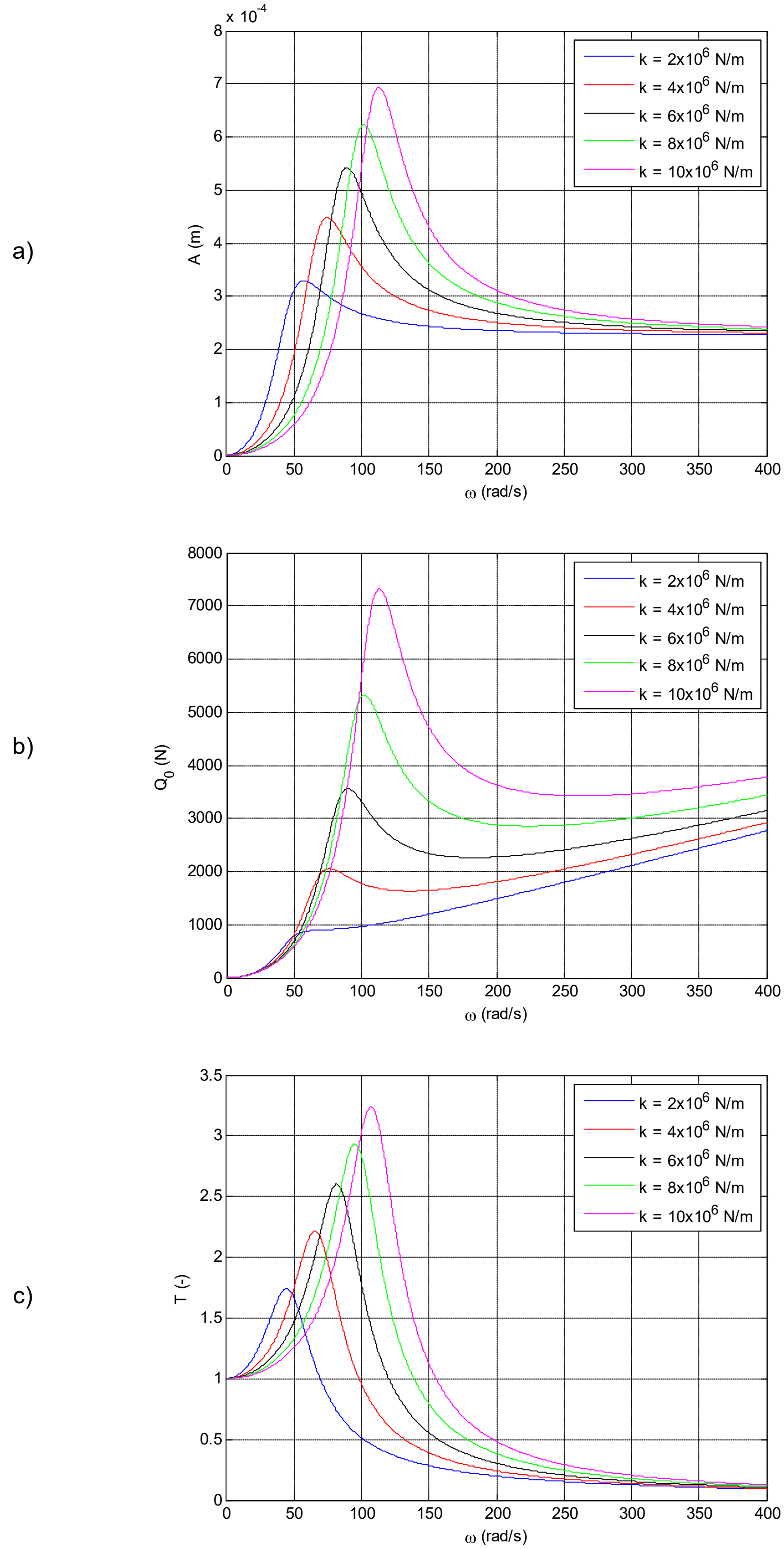


Fig. 5.11 The variation of vibration amplitude *A*, the force transmitted to the terrain Q_0 and the transmissibility *T* in relation to the pulsation of the exciting source. The first simulation scenario in case 2

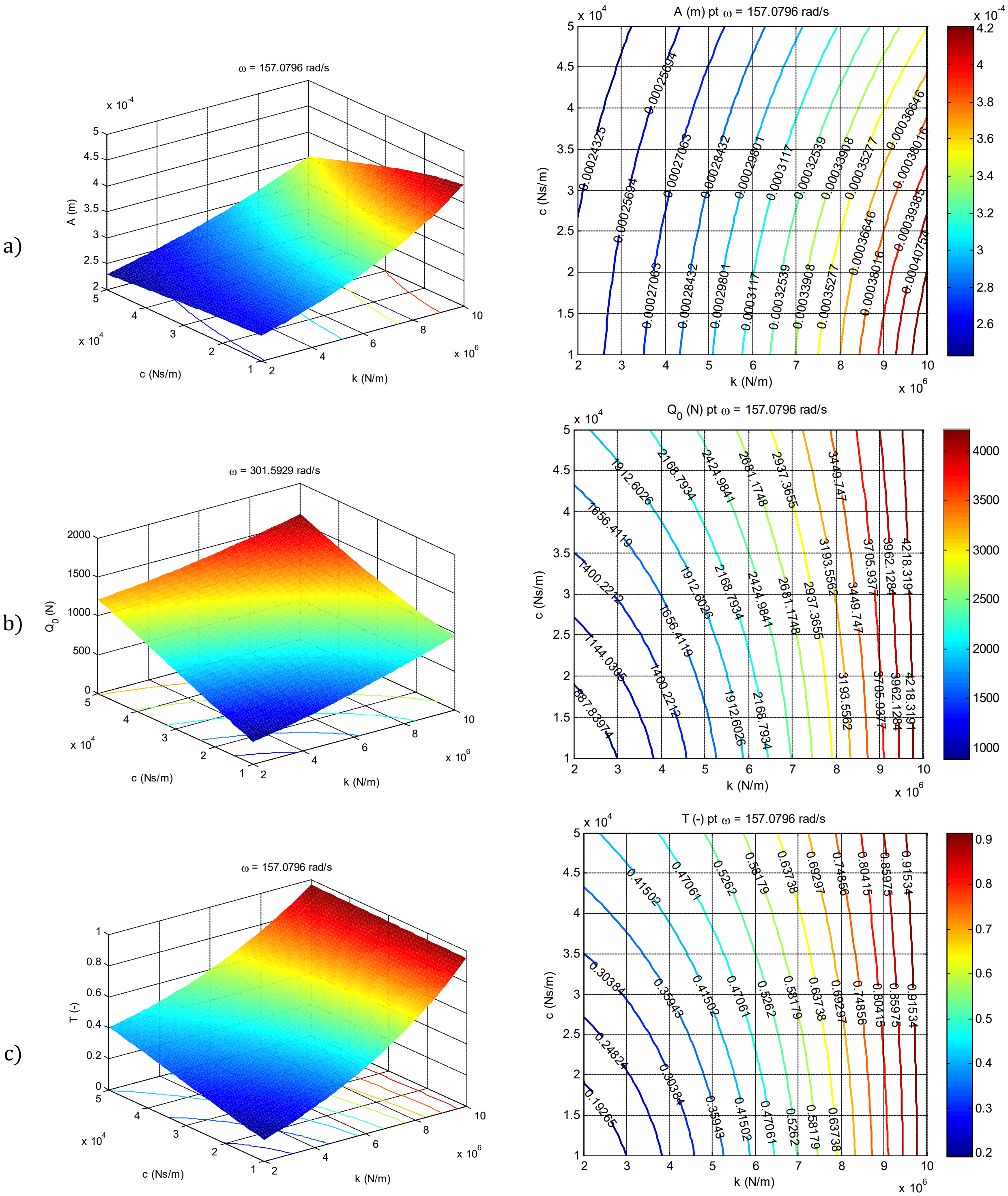


Fig. 5.12 The vibration amplitude variation *A*, the force transmitted to the terrain Q_0 and the transmissibility *T* relative to terrain stiffness and damping. The first simulation scenario in case 2

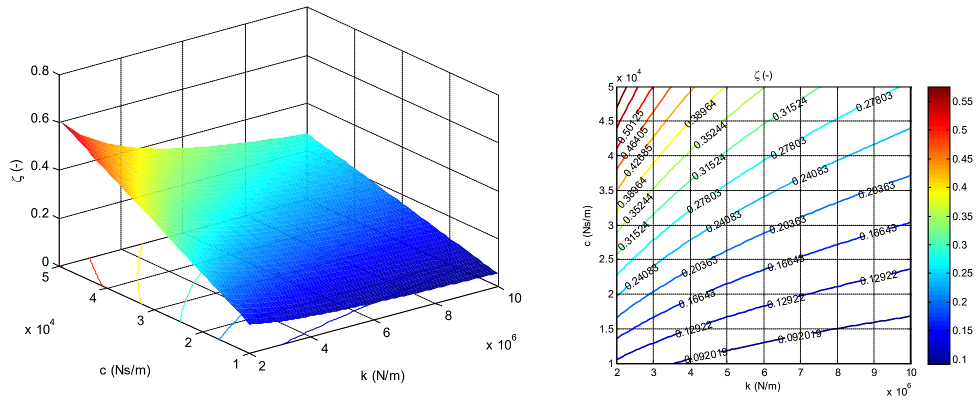
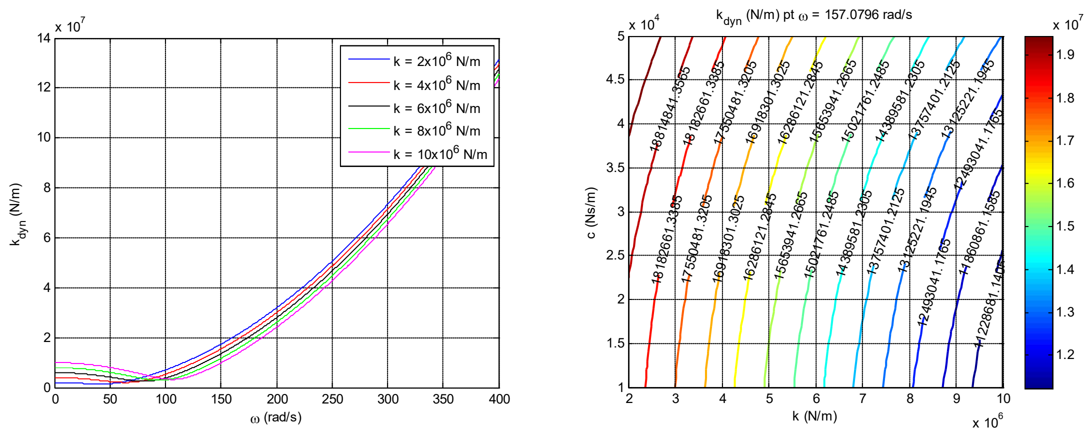
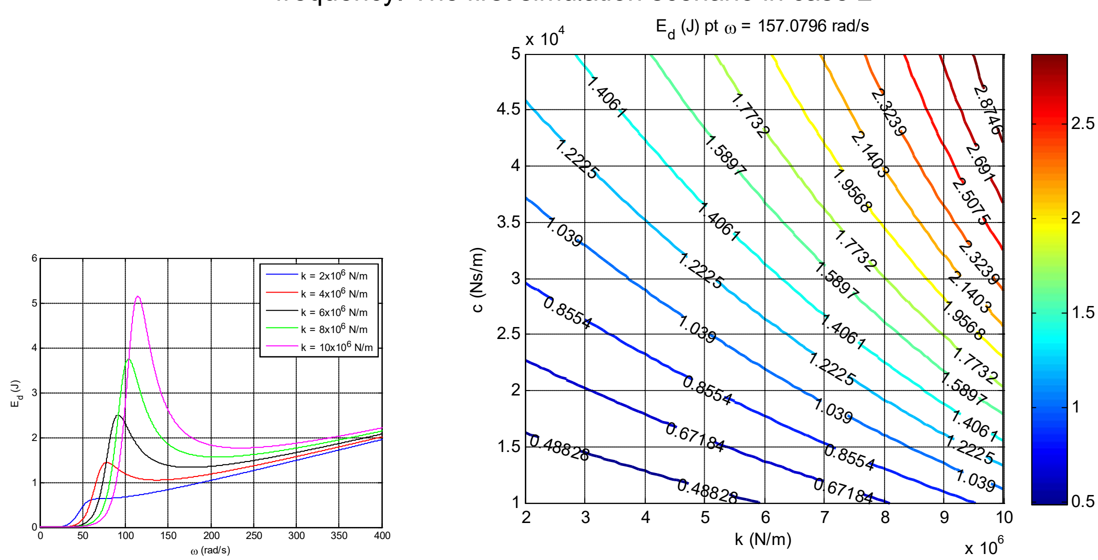


Fig. 5.13 Variation of critical damping fraction with respect to terrain stiffness and damping. The first simulation scenario in case 2



a) b)

Fig. 5.14 Variation of dynamic stiffness according to:
a) pulsation of the exciting source; b) stiffness and damping of the terrain for the working frequency. The first simulation scenario in case 2



a) b)

Fig. 5.15 The variation of energy dissipated in the terrain according to:
a) pulsation of the exciting source; b) stiffness and damping of the terrain, for the working frequency. The first simulation scenario in case 2

In the second simulation scenario, both the damping coefficient *c* and the critical damping fraction ζ_i, corresponding to each passage of the machine over the layer, were varied with distinct values, and the curves represented in figures 5.13 were obtained through numerical simulation and 5.14 for the two working regimes of the vibratory roller of the compactor.

Table 5.3. Identification data of the second simulation scenario in case 1

Initial terrain data
- soil category: filling soil, weakly cohesive - static elastic modulus: E_{st} = 139,4 daN/cm^2 - critical damping ratio: ζ=0,16 - initial compaction degree: D_i =0,8567
Initial vibratory drum data
-drum mass: m= 830 kg -static moment: $M_{st}=m_0r$=0.066 kgm -excentricity: r = 0,066 m -excentricity masses: m_0 = 1 kg -width drum: B=0.80 m -drum diameter: D_r=0.62 m -frequency vibration in working regime: f = 48 Hz -dynamic force: F_0= 6480 N -roller speed in working regime: V_{max}=1.44 km/h
Initial drum roller – terrain interaction data
- fast working regime: with high frequency vibrations - type interaction modeling with Voigt-Kelvin model: ζ=0.16, ζ=0.24, ζ=0.42, ζ=0.50, ζ=0.70

Table 5.4. Identification data of the second simulation scenario in case 2

Initial terrain data
- soil category: filling soil, weakly cohesive - static elastic modulus: E_{st} = 139,4 daN/cm^2 - critical damping ratio: ζ=0,16 - initial compaction degree: D_i =0,8567
Initial vibratory drum data
-drum mass: m= 830 kg -static moment: $M_{st}=m_0r$=0,187 kgm -excentricity: r = 0,187 m -excentricity masses: m_0 = 1 kg -width drum: B=0.80 m -drum diameter: D_r=0.62 m -frequency vibration in working regime: f = 25 Hz -dynamic force: F_0= 6480 N -roller speed in working regime: V_{max}=1.44 km/h
Initial drum roller – terrain interaction data
-slow working regime: with low frequency vibrations - type interaction modeling with Voigt-Kelvin model: ζ=0.16, ζ=0.24, ζ=0.42, ζ=0.50, ζ=0.70

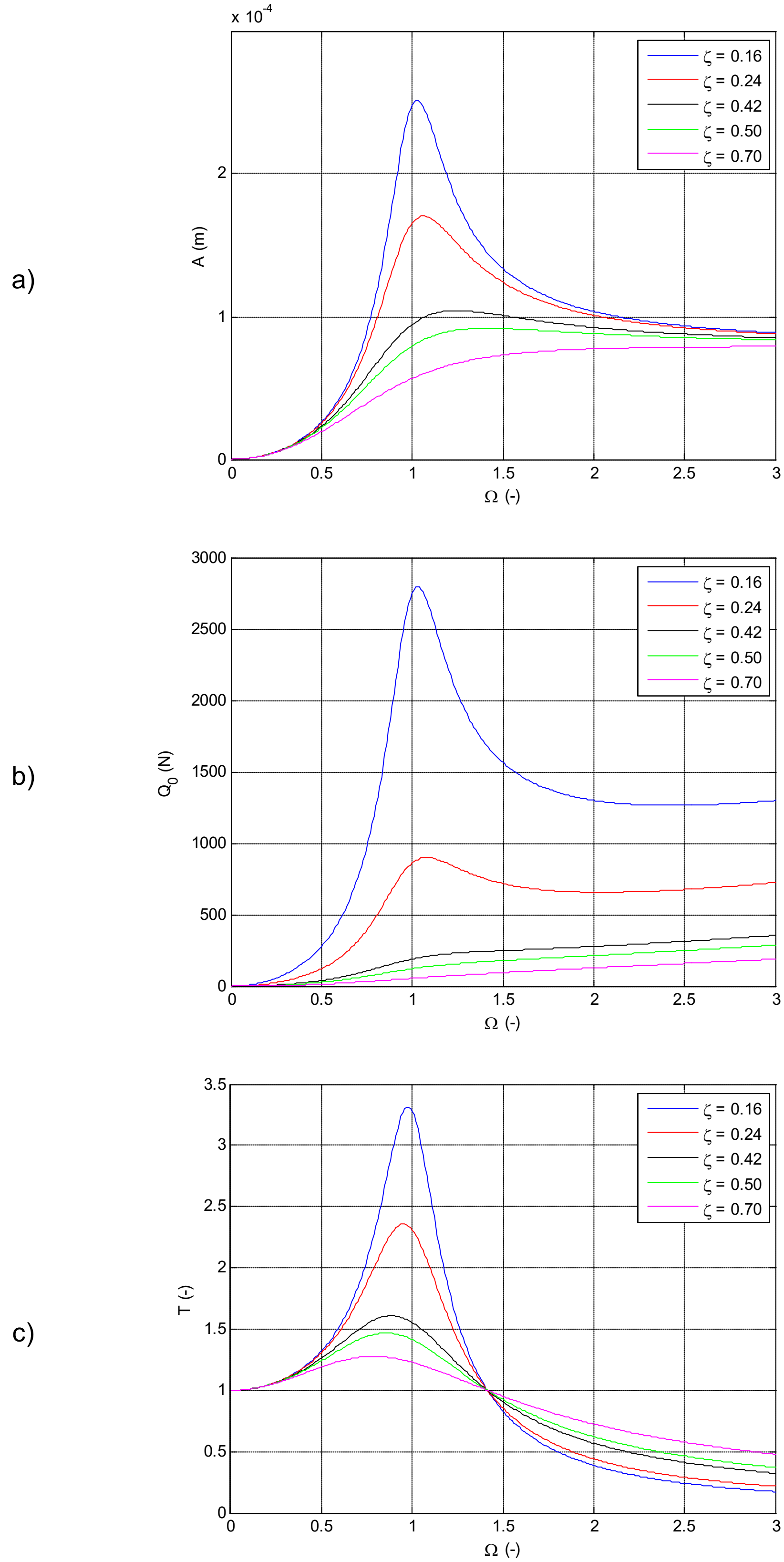
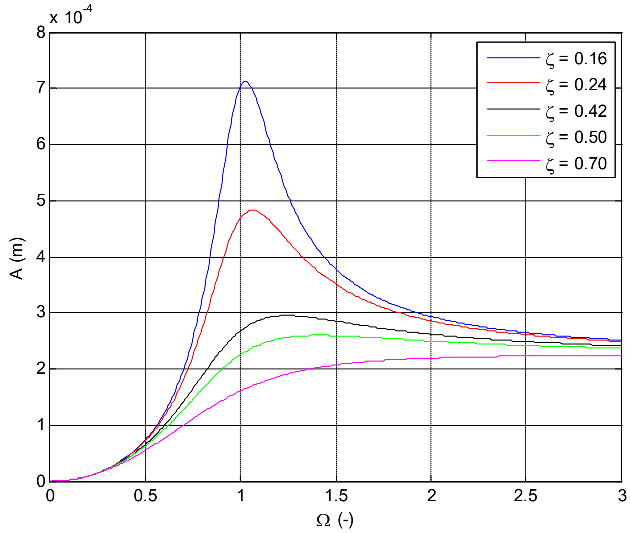
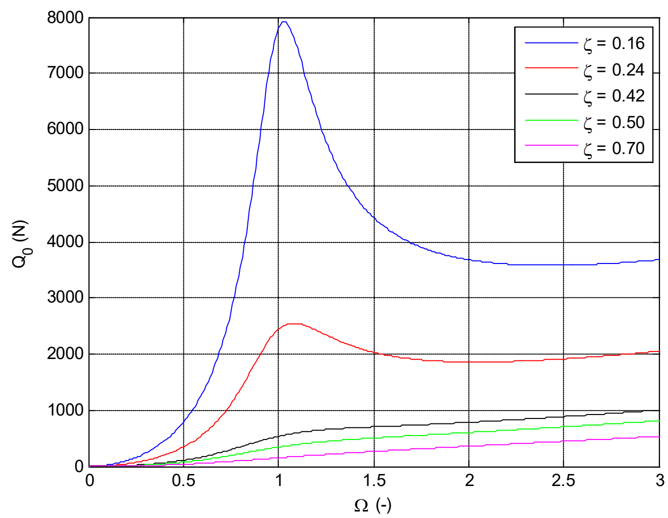


Fig. 5.16 The variation in vibration amplitude *A*, the force transmitted to the terrain Q_0 and the transmissibility *T* in relation to the pulsation ratio. The second simulation scenario in case 1

a)



b)



c)

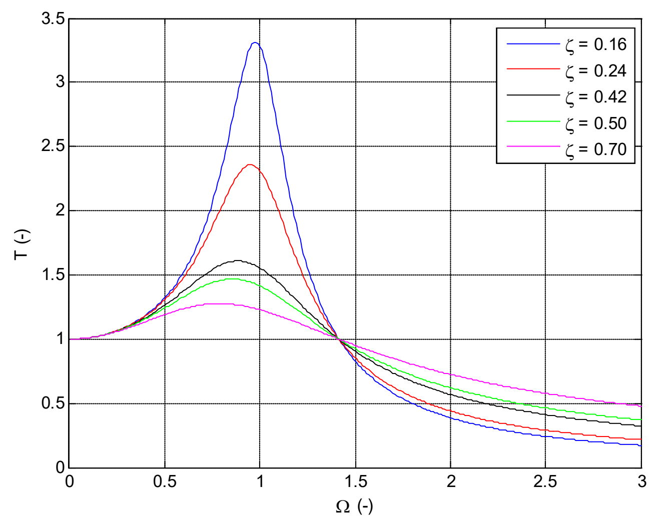


Fig. 5.17 The variation in vibration amplitude *A*, the force transmitted to the terrain Q_0 and the transmissibility *T* in relation to the pulsation ratio. The second simulation scenario in case 2

5.2.5. Partial conclusions

In conclusion, for the viscoelastic modeling of fill soils, weakly cohesive, it is recommended to choose the Voigt-Kelvin rheological model with the help of which, by varying the characteristic parameters of the soil k and c (to fit the model with the measured data of the soil condition in the initial phase, corresponding to the measurement points F - I) and the technological equipment used to perform compaction F_0 and ω, it is possible to numerically simulate the performance of a vibration compaction process in two distinct working states specific to the technological regime in terms of the field of vibrations, respectively: in pre or post resonance. From the results obtained by simulation and validated by the experimental results from the measurement points F - I, two defining aspects were highlighted for the use of this rheological model in the modeling of the vibration compaction process, namely:

a) the predominantly elastic behavior of the Voigt-Kelvin rheological model;
b) the ratio between the excitation of the vibration source of the technological equipment and the physical-mechanical parameters of the terrain generates dynamic effects and the appearance of the resonance phenomenon, but with insignificant values on the behavior of the compactor-terrain system.

5.3. Simulation of the static compaction process based on the proposed theoretical model (MTC) for characterizing the behavior of a terrain when the initial geotechnical parameters are known

5.3.1. Specifications about the input data in the algorithm of the MTC model

The program imput data are:

a) geotechnical parameters for characterizing the terrain and the initial state of compaction;

b) characteristic roll-ground contact parameters;

c) the parameters that define the working regime of the compactor used, according to the working technology adopted;

d) the interparametric laws established between the specific parameters of the compaction process (identified in subchapter 4.3 of the doctoral thesis).

For the correct interpretation of the results obtained by simulation and those presented in the compaction steps, the following clarifications are necessary:

- the stress durations under load t and the settlements Δh_i refer to the current passing ,,*i*,,;
- the required number of passes is considered as the number of passes for which the maximum value of the soil stiffness coefficient k_{max} is exceeded, which corresponds to the maximum values that can be achieved for the parameters ρ_d, E_{st} and D_i (the actual values achieved in the field for these parameters are known through specific experimental investigations, described in detail in chapter 3 of the doctoral thesis);
- the pressure p that develops in the terrain, considered, represents the pressure at the beginning of the compaction process (that is, the one obtained at the current pass), being realized in practice at the end of the previous pass;
- settlement Δh is a cumulative value of settlements Δh_i made after previous passes and after the current pass;
- the values of the parameters (the degree of compaction D_i, the dry state density of the terrain ρ_d, the static modulus of longitudinal deformation E_{st}) are values obtained after the current pass;
- the degree of compaction determined corresponds to the conditions of the normal Proctor test, in which the value of the specific mechanical work of compaction is 6 dJ/cm^3;

– the technological compaction load, quantified by the degree of compaction necessary to reach D_{i_nec}, is considered to be the maximum value possible to reach for the work technology used, a value that corresponds to a state of terrain compaction characterized by reaching the maximum value of the stiffness coefficient k_{max} of the terrain.

5.3.2. Simulation results

To simulate the behavior of the terrain based on the proposed model, a work scheme was developed in Matlab/Simulink (fig. 5.18) in which the initial geotechnical data of the terrain from the measurement point F were input, together with the interparametric laws from subchapter 4.3.

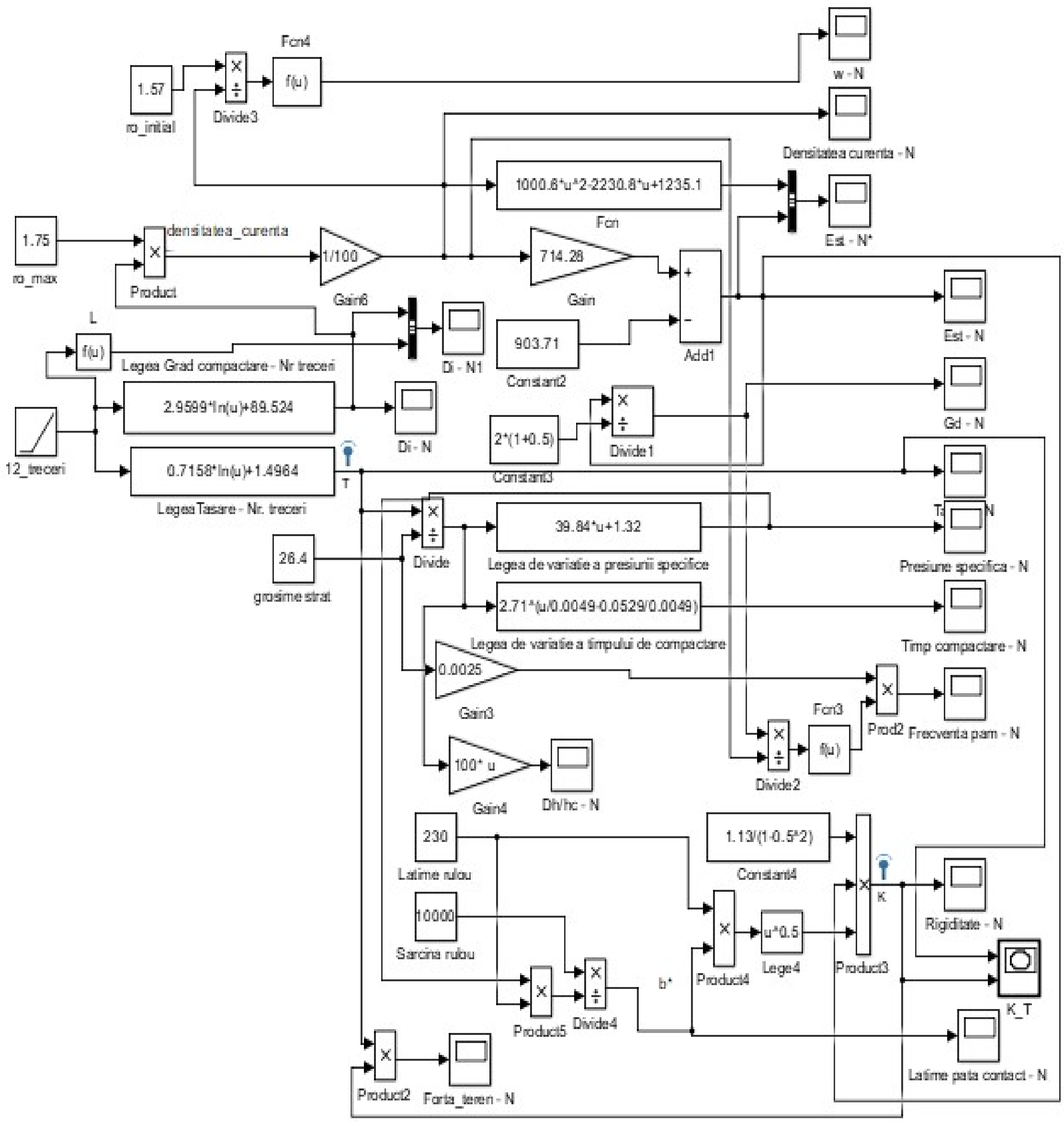


Fig. 5.18 Worksheet for the simulation of the overall performance of the compaction of a terrain corresponding to that of the measurement point F (MTC model)

The proposed scheme is one that can be generalized, in the sense of introducing the initial values of the geotechnical determinations of the terrain completed with the interparametric laws corresponding to another case of compaction that is desired to be analyzed.

All the results obtained are presented in Figures 5.19 - 5.21, through a set of diagrams of the variation of the main parameters of the land depending on the resulting degree of compaction and the settlement achieved.

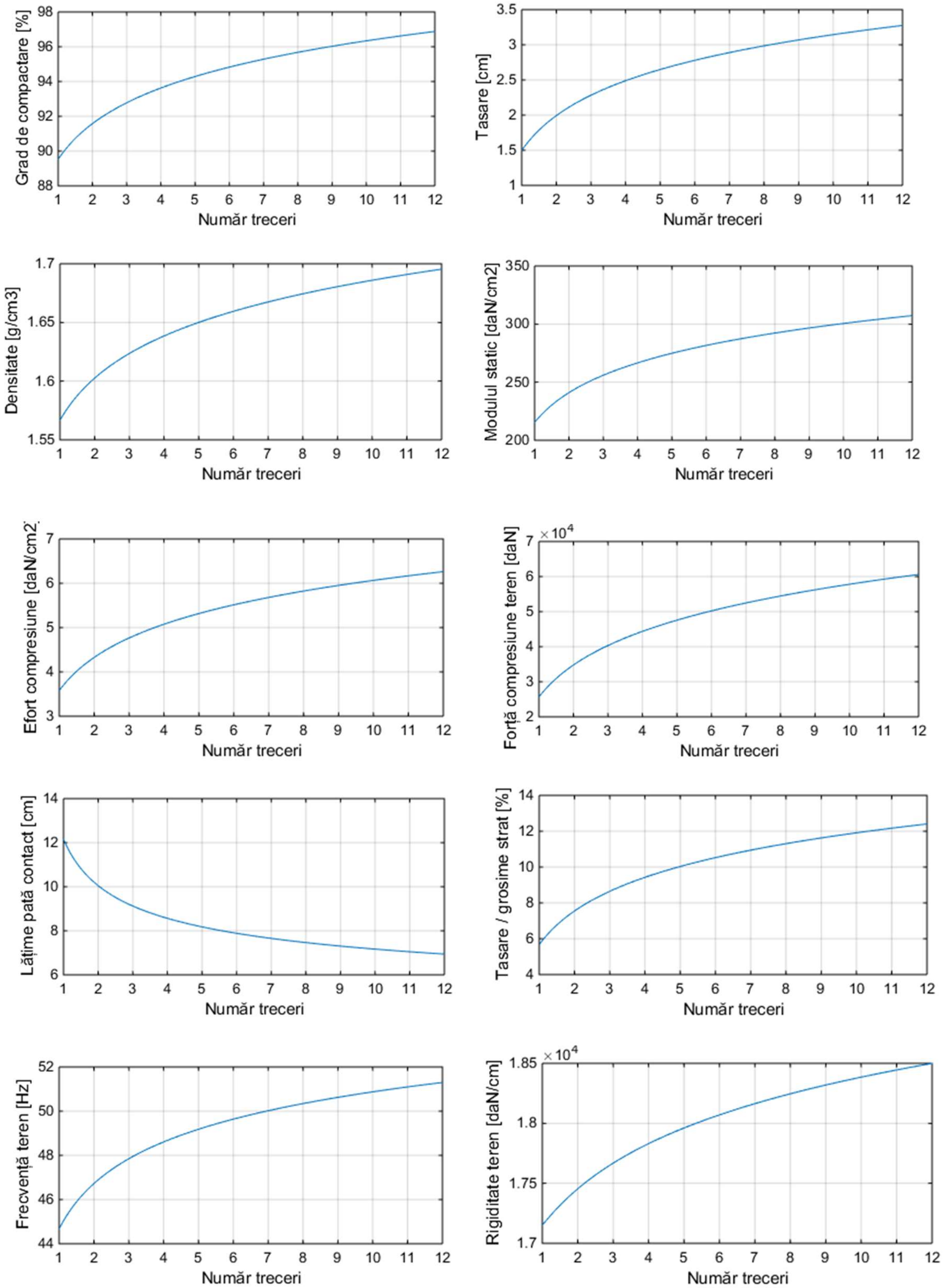


Fig. 5.19 The variation of the specific parameters necessary to identify the performance of the compaction process

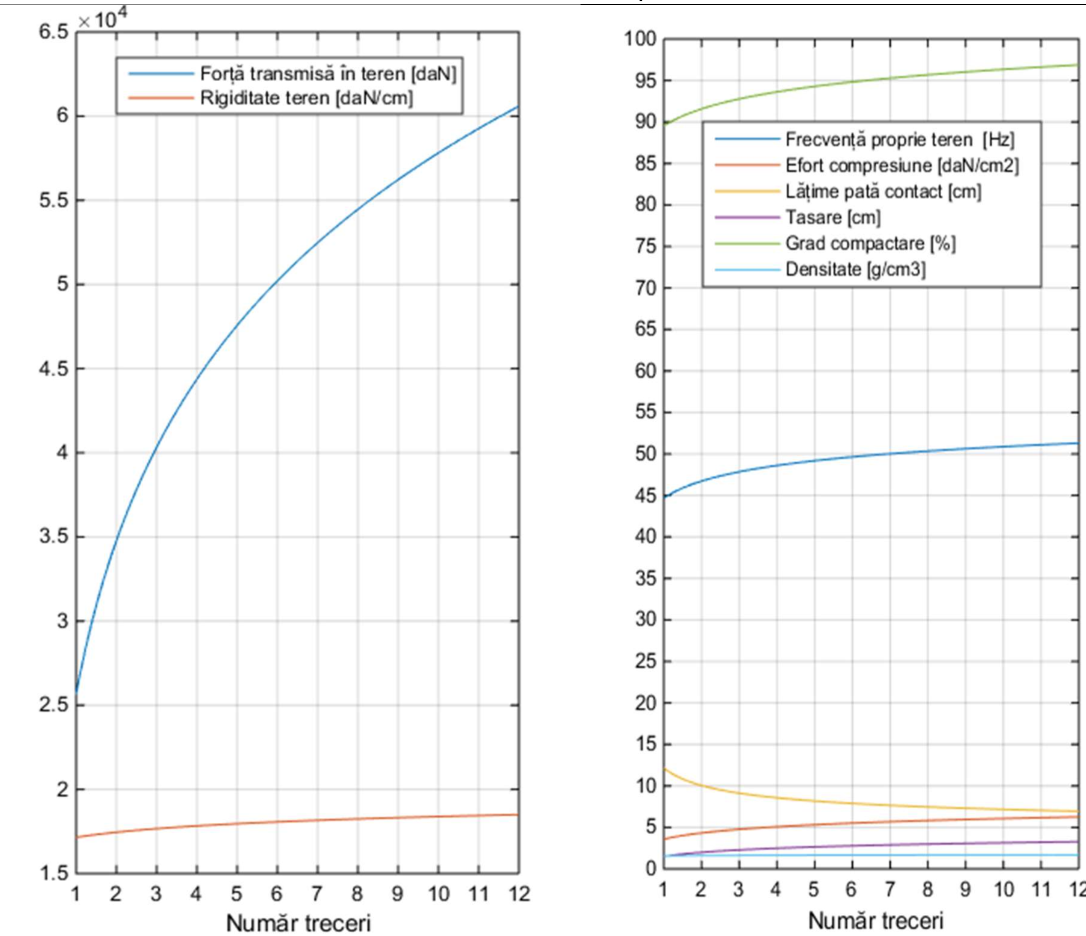


Fig. 5.20 The overall view of the variation of the specific parameters necessary to identify the performance of the compaction process

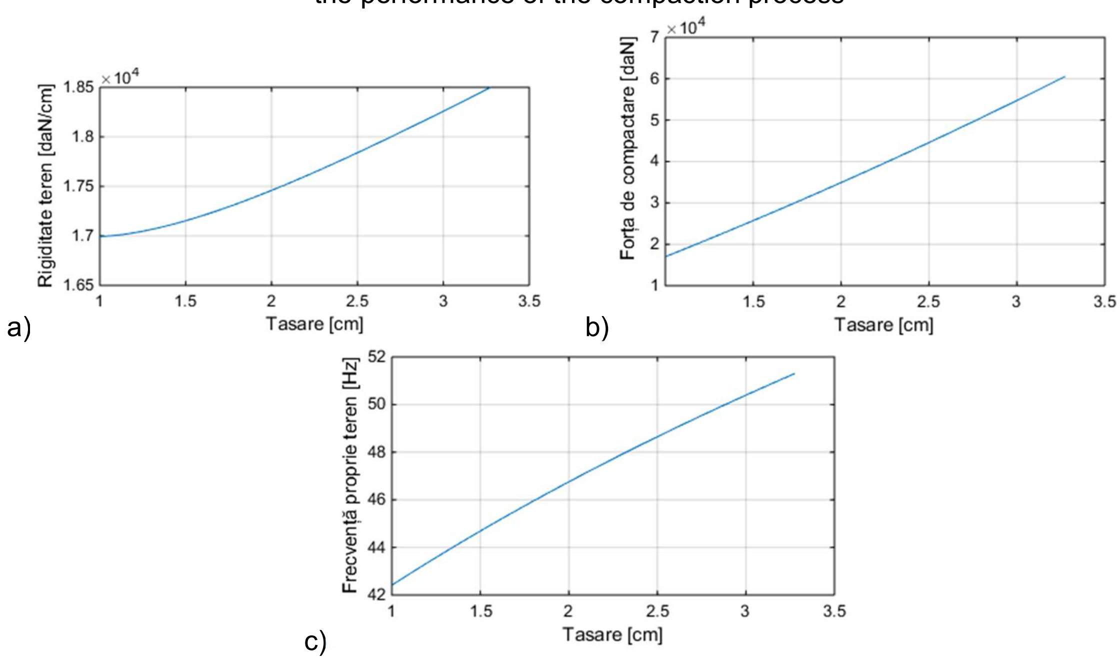


Fig. 5.21 Identification of the response of the terrain during the compaction process, through the evolution of its specific parameters:
a) stiffness coefficient; b) compaction force; c) natural frequency.

5.3.3. Partial conclusions

The primary experimental data resulting from in situ determinations and laboratory investigations, processed and synthesized in the form of final results, compared with the results obtained from the simulation of the compaction process based on the theoretical model of soil behavior, are presented in Table 5.6.

Table 5.6 Analysis of the results obtained on the theoretical model vs. experimental investigations

Point (in situ)	Passes number *N*		Compaction degree D_i [%]		Density (dry) ρ_d [g/cm^3]		Static longitudinal modulus, E_{st} [daN/cm^3]		Settlement terrain, Δh [cm]	
	Model	Real	Model	Real	Model	Real	Model	Real	Model	Real
F	12	12	96,8	94,57	1,69	1,655	305	274	3,27	3,245

The obtained results allow synthesizing the following final conclusions regarding the theoretical soil behavior model (SRM):

- the model adapts correctly to real work situations, the values indicated for the modeled parameters being close to those that describe the optimal technological situation;
- there is a good correlation between the values of the final main parameters of the modeling vs reality compaction processes (in terms of number of passes, degree of compaction, dry density, longitudinal static modulus, settlement);
- the model can be used for relevant estimates in the design and technological preparation phases of the compaction processes, for weakly cohesive soils, offering the advantage of knowing the correlation between the change in the stiffness coefficient of soil depending on the evolution of the soil condition (through the amount of settlement achieved).

5.4. Modeling and simulation of behavior of weakly cohesive soils in compaction process, highlighting settlement on rheologic models (MRTTC, EVP)

5.4.1. The MRTTC model description

Taking into account the previously presented aspects, a rheological model (Figure 5.22) is proposed that has visco-elastic and dissipative behavior (called MRTTC), useful in carrying out a numerical simulation with the main objective of highlighting the way in which it behaves a weakly cohesive soil under the action of a roll of a self-propelled compactor.

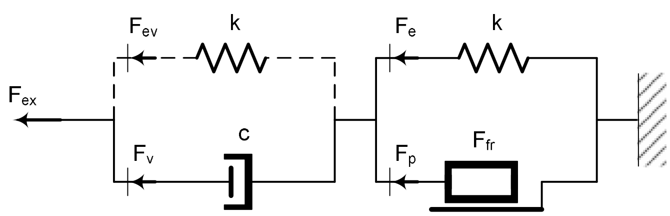


Fig. 5.22 Rheological model for the simulation of roller-terrain interaction in the vibration compaction process

5.4.2. Simulation results

Based on the measurements made at the measuring point marked with F, simulations were made of the response of the terrain to the action of the compactor roller (VV-170), corresponding to the 12 passes over the same layer of soil (with an initial thickness of 26.4 mm), an aspect that must be understood as a continuous evolution of increasing the degree of compaction. The results obtained through the numerical simulation in the Matlab programming environment are given in figures 5.25 – 5.27, in the form of graphs that indicate the way of variation of the total deformation and, respectively, by components (elastic, plastic, viscous) of the compacted layer in response to the action of the compactor roller that moved with constant speed and parameters of the working regime. For the simulated case, the change in the width of the contact spot after each of the 12 passes of the roller was taken into account, taking into account the variation law (4.6) validated and the approximation laws centralized in table 4.11.

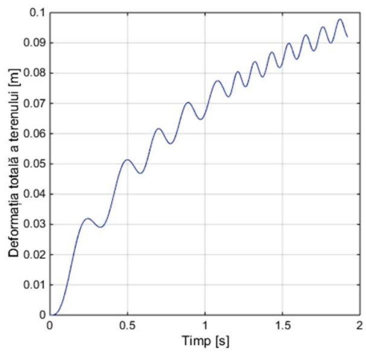


Fig. 5.25 The variation of the total deformation transmitted to the ground in response to the action of the roller

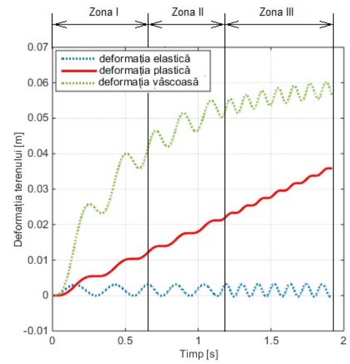


Fig. 5.27 Identification of areas of interest for the analysis of the terrain compaction process

The description of the significance of each area identified in fig. 5.27 is [85]:

- Zone I: zone with large deformations in response to the stresses transmitted by the roller in the terrain, especially plastic deformations (settlement / consolidation) and those of a viscous nature (frictions in the internal structure of the material subject to compaction);
- Zone II: zone with average deformations of the plastic and viscous components, with an increasing trend of the recorded values;
- Zone III:zone with small deformations for plastic and viscous components, with a tendency towards a constant value of the latter and with a very small increase in settlement.

However, the behavior of the elastic deformation is noted, which is in the form of an oscillatory movement with different frequency during the soil compaction process. Thus, in zone I, the frequency of oscillations is low due to the loose state of the terrain, and it follows that in zone III, where the land is rigid, a vibratory behavior with increased frequency can be identified. During all this time of the compaction simulation process, amplitude of the elastic deformation is kept constant.The viscous deformation of the after each pass is difficult to capture in the numerical simulation process, since it has a specific evolution over a much longer time duration than the one on which the simulation is made (see long time duration between passes-fig.5.28, 5.29) [85].

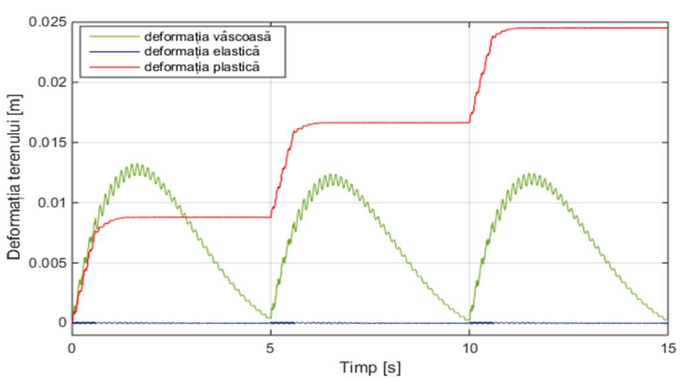


Fig. 5.28 Simulation of the terrain response (modeled according to the one at the measurement point F) in terms of its deformations, after the first 3 passes

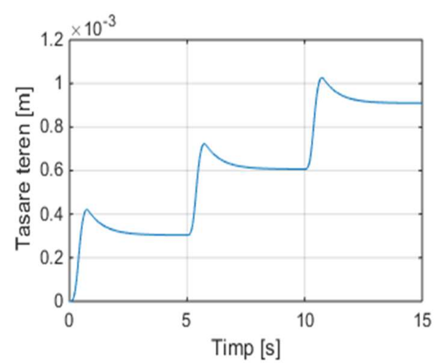


Fig. 5.29 Simulation of the terrain response (from G and H) after the first 3 passes

5.4.3. Partial conclusions

The working principle during a cycle ,,*i*,, of the action of the dynamic force of the vibrating roller (corresponding to the contact duration t_{ci} during a period of action of the load) consists in the following sequence of dynamic behaviors of the proposed model, thus:

- ***dynamic behavior in the elasto-plastic deformation regime of the material***: from the moment the excitation force exceeds the threshold value of the static friction force, the model highlights both the elastic and plastic deformations that appear in the rheological elements. This movement is maintained until the instantaneous value of the excitation force begins to decrease and reaches the threshold value of the friction force;
- ***dynamic behavior in the plastic deformation regime of the material***: when the excitation force continues to decrease, the terrain stores residual deformation which is actually the corresponding initial settlement obtained during the work cycle ,,*i*,, analyzed;
- ***dynamic behavior in the regime of elastic return of the material***: when the value of the excitation force falls below the limit value of the consolidation (settlement) force, then the behavior of the material consists of an elastic return (movement that occurs because the value of the force accumulated in the elastic element increases above the threshold value of the frictional force in the dissipative element and in this way conditions it to move in the direction of the relaxation of the elastic element). This regime of returning to a state of structural equilibrium, called the normalization regime, evolves until the moment when the value of the excitation force begins to increase and again equals the limit value of the consolidation force;
- ***dynamic behavior in the material's consolidated plastic regime***: after the moment when the excitation force becomes equal to the material's consolidation force, it no longer allows deformations to occur in its structure. The duration of this regime is completed when the exciting force of the roll reaches the threshold value of the static friction force specific to the material. In the situation where the limit of consolidation on the considered cycle "*i*" is not obtained over the entire range of action in which the exciting force has values lower than the threshold value of the static friction, it follows that the material changes its behavior specific to the elasto-plastic regime directly in a behavior specific to the consolidated plastic regime;
- cycle ,,i +1,, is carried out in the same way as previously described, specifying that, at the completion of each complete cycle, the value of the limit strength of consolidation will increase by the value ΔF (different according to the material), until it is reached limit value of static friction force. At that moment, the consolidation process is completed, and the material continues to take on external loads only with the elastic component. From the analysis of the experimental data, it is found that after 8 successive passes of the machine, on the same layer, the settlement value tends asymptotically towards a limit value characteristic of the respective layer.

The results obtained by simulation support the results obtained on the experimental one, presented in the previous chapters of the thesis, regarding the evolution of the settlement of a weakly cohesive soil under the static action of a compactor roller (case study on the measurements at point F).

5.4.4. Description of the EVP model

In this sub-chapter of the thesis, the author considered two other types of rheological models to analyze the behavior of soil subjected to vibration compaction.

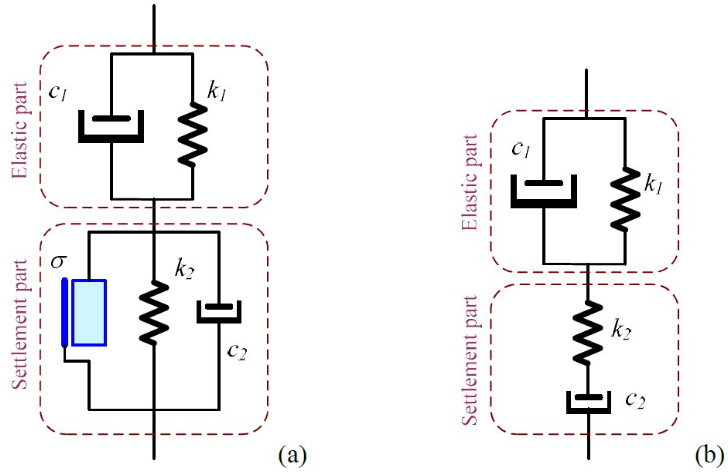


Fig. 5.30 Schematic diagrams for the rheological models used for simulation terrain settlement [86]:
a) viscous-elasto-plastic model (EVP); b) model derived from Burgers model.

According to the schematization of the EVP model in figure 5.30a, the response of the elastic component can be formulated as follows

$$x_1 = F(k_1 + c_1\Delta)^{-1}\,, \tag{5.18}$$

at the same time, the settlement response can be expressed as an interval function

$$x_2 = \begin{cases} (F - F_{lim})(k_2 + c_2\Delta)^{-1} & dacă\ F > (k_2 + c_2\Delta)x_{2,(j-1)} > F_{lim}, sgn(\dot{x}_{2,(j-1)}) \geq 0 \\ 0 & dacă\ F \leq (k_2 + c_2\Delta)x_{2,(j-1)} \leq F_{lim}, sgn(\dot{x}_{2,(j-1)}) \geq 0 \\ (F + F_{lim})(k_2 + c_2\Delta)^{-1} & dacă\ (k_2 + c_2\Delta)x_{2,(j-1)} > F > F_{lim}, sgn(\dot{x}_{2,(j-1)}) < 0, \\ 0 & dacă\ (k_2 + c_2\Delta)x_{2,(j-1)} \leq F \leq F_{lim}, sgn(\dot{x}_{2,(j-1)}) < 0 \end{cases} \tag{5.19}$$

where *F* represents external dynamic excitation, $k_{1,2}$ and $c_{1,2}$ are rigidity and, respectively, damping coresponding to constitutive parts of the models, $F_{lim}=\sigma$ is the plasticity parameter (in term as limited force that allows or not to move the contact), Δ is the derivative operator in respect to time. The subscript (j-1) in the conditional inequalities indicates that evaluation will be done in relation to the value reached in the previous calculation step. Taking into account that model response is the sum of the two partial displacements $x_{1,2}$, equivalent stiffness of the EVP model is

$$k_e = \begin{cases} \frac{(k_1+c_1\Delta)(k_2+c_2\Delta)}{(k_2+c_2\Delta)+(k_1+c_1\Delta)(1-F_{lim}/F)} & dacă\ F > (k_2 + c_2\Delta)x_{2,(j-1)} > F_{lim}, sgn(\dot{x}_{2,(j-1)}) \geq 0 \\ (k_1 + c_1\Delta) & dacă\ F \leq (k_2 + c_2\Delta)x_{2,(j-1)} \leq F_{lim}, sgn(\dot{x}_{2,(j-1)}) \geq 0 \\ \frac{(k_1+c_1\Delta)(k_2+c_2\Delta)}{(k_2+c_2\Delta)+(k_1+c_1\Delta)(1+F_{lim}/F)} & dacă\ (k_2 + c_2\Delta)x_{2,(j-1)} > F > F_{lim}, sgn(\dot{x}_{2,(j-1)}) < 0 \\ (k_1 + c_1\Delta) & dacă\ (k_2 + c_2\Delta)x_{2,(j-1)} \leq F \leq F_{lim}, sgn(\dot{x}_{2,(j-1)}) < 0. \end{cases} \tag{5.20}$$

According to the Burgers-based model in figure 5.30b the equivalent stiffness is:

$$k_e = \frac{k_2c_2\Delta(k_1+c_1\Delta)}{(k_2+c_2\Delta)(k_1+c_1\Delta)+k_2c_2\Delta}. \tag{5.21}$$

The analyzes were performed based on the spectral evaluation of the responses of both models. Thus, the equations of the two models were transferred to the complex domain. Input the notations $\tau_1 = c_1 / k_1$, $\tau_2 = c_2 / k_2$ for the time constants of the viscoelastic parts of the EVP model, relation (5.20) can be written as

$$k_e = \begin{cases} \frac{k_1(1+i\omega\tau_1)k_2(1+i\omega\tau_2)}{k_2(1+i\omega\tau_2)+k_1(1+i\omega c\tau_1)(1-F_{lim}/F)} & dacă\ F > (k_2 + c_2\Delta)x_{2,(j-1)} > F_{lim}, sgn(\dot{x}_{2,(j-1)}) \geq 0 \\ k_1(1 + i\omega\tau_1) & dacă\ F \leq (k_2 + c_2\Delta)x_{2,(j-1)} \leq F_{lim}, sgn(\dot{x}_{2,(j-1)}) \geq 0 \\ \frac{k_1(1+i\omega\tau_1)k_2(1+i\omega\tau_2)}{k_2(1+i\omega\tau_2)+k_1(1+i\omega\tau_1)(1+F_{lim}/F)} & dacă\ (k_2 + c_2\Delta)x_{2,(j-1)} > F > F_{lim}, sgn(\dot{x}_{2,(j-1)}) < 0 \\ k_1(1 + i\omega\tau_1) & dacă\ (k_2 + c_2\Delta)x_{2,(j-1)} \leq F \leq F_{lim}, sgn(\dot{x}_{2,(j-1)}) < 0. \end{cases}, \tag{5.22}$$

and equation (5.21) of the Burgers-based model thus

$$k_e = \frac{k_2 i\omega\tau_2 k_1(1+i\omega\tau_1)}{k_2 i\omega\tau_2 + k_1(1+i\omega\tau_1)(1+i\omega\tau_2)}, \tag{5.23}$$

where $i^2 = -1$ and ω is the excitation frequency.

The numerical values used in the calculation analyzes are: $m_o r$ = 5.7 kgm, k_1 = 10e6 N/m, k_2 = 14e6 N/m, c_1 = 0,75e3 Ns/m, c_2 = 20e3 Ns/m, $\sigma = F_{lim}$ =1e5 N.

5.4.5. Simulation results

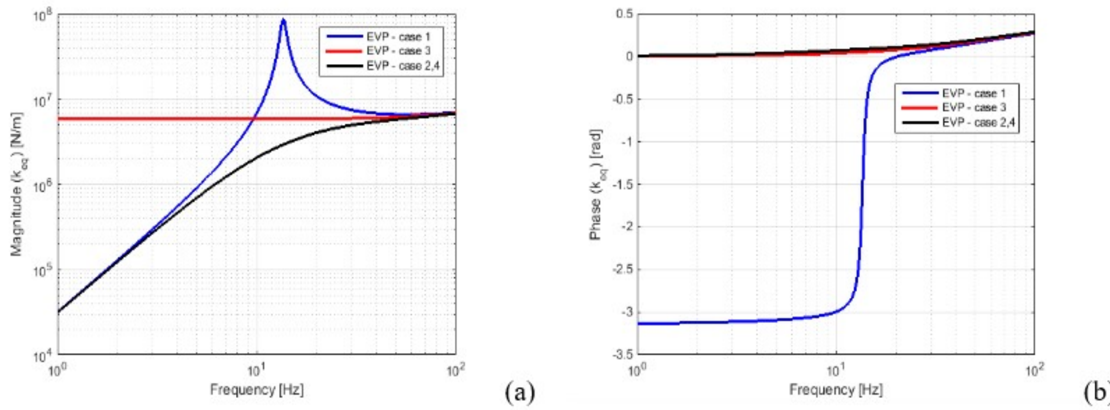


Fig. 5.31 The response spectrum of the EVP model components in terms of: a) amplitude; b) phase

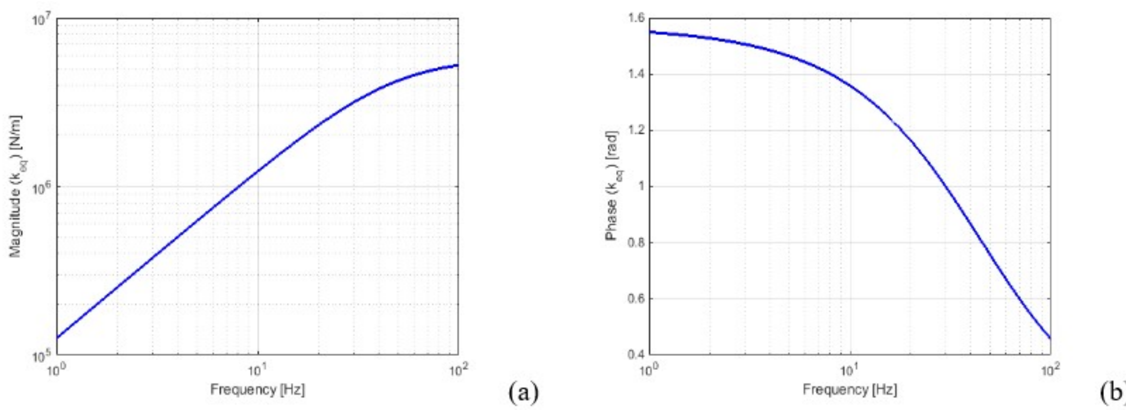


Fig. 5.32 The response spectrum of the model derived from Burgers in terms of: a) amplitude; b) phase

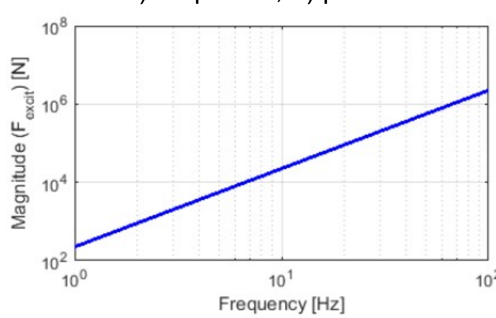


Fig. 5.33 The spectral magnitude of the external excitation force

The magnitude peak (Fig. 5.34a, EPV case 1) results from the presence of the term (1-F_{lim}/F) in the denominator, which leads to a substantial reduction at the moments when the excitation becomes equal to the plasticity limit. The evolution of this case has a sudden phase change by π radians (Fig. 5.34b).

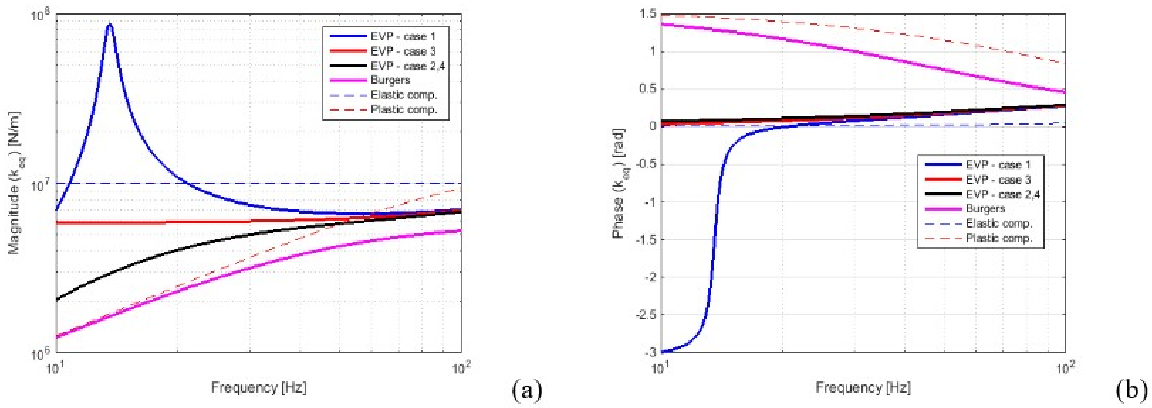


Fig. 5.34 The response spectrum of the models in terms of:
a) amplitude; b) phase

A comparative analysis was carried out using the overlapped diagrams for both rheological models, for a minimum value of 10 Hz of the excitation frequency, the admittance function being evaluated for both models, and the result, in the form of amplitude, is given in figure 5.35.

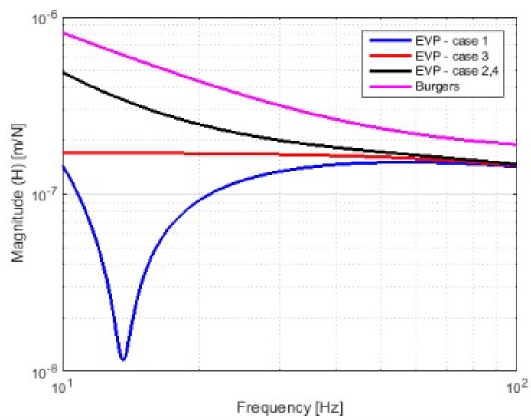


Fig. 5.35 Spectral magnitude of the admittance function with respect to the model components

It is observed that the general trend of decreasing the admittance magnitude is respected by all the components of the model.

5.4.6. Partial conclusions

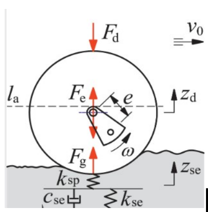
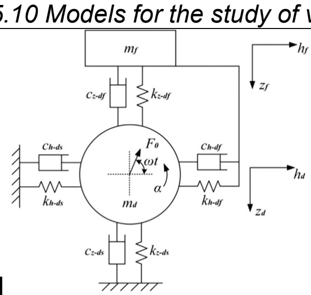
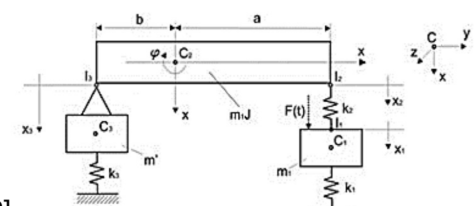
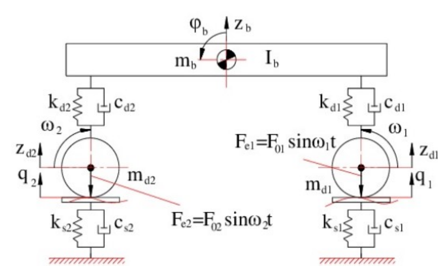
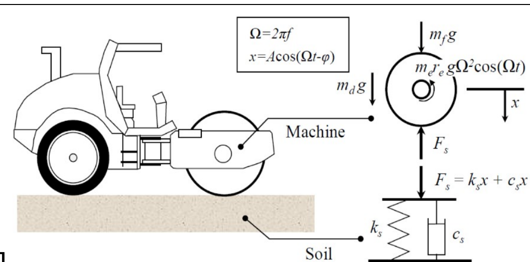
The results obtained on the EVP model, in terms of equivalent stiffness and admittance function, are very useful for the calculation algorithm in predictive computational models in automatic systems implemented on modern compactors. These models are used for continuous adjustment of the parameters of the working regime of the technological equipment with the local characteristic of instantaneous terrain settlement, to obtain the imposed settlement after a minimum number of passes. Thus, the estimated response of the terrain during the work cycle can be continuously evaluated and the working parameters of the equipment can be changed instantly. The analysis highlights the fact that the dissipative viscous component of the terrain affects the evolution of the equivalent stiffness with respect to the excitation frequency. At the same time, the plastic component induces relatively sudden changes in the local stiffness with direct implication on the dynamic response. These observations underline the importance of nonlinear models in the analysis of the vibratory roller - compacted soil interaction, especially for the optimization of technological equipment.

5.5. Modeling and dynamic simulation of ground-roller interaction using multi-degree-of-freedom models (MRIETC 1, MRIETC 2)

5.5.1 The stage of knowledge

Taking into account the research direction of this PhD thesis, in order to achieve a technological performance requirement imposed on the compaction process, dynamic models developed for the study of the interaction between the compaction equipment and the terrain will be presented. In the specialized literature there are numerous bibliographic references (table 5.10) with useful models for simulating the dynamic behavior of compactors with different constructive forms.

Table 5.10 Models for the study of vibratory compactor - soil interaction

 [87]	 [89]	 [93]
 [94]	 [92]	

5.5.2 Modeling and simulation of single roller tire compactors (MRIETC 1)

The VV-170 compactor was used for the soil compaction works carried out on the experimental site on runway 1, and therefore an equivalent dynamic model (MRIETC) will be developed to simulate the response of the soil to the action of the machine (fig. 5.36).

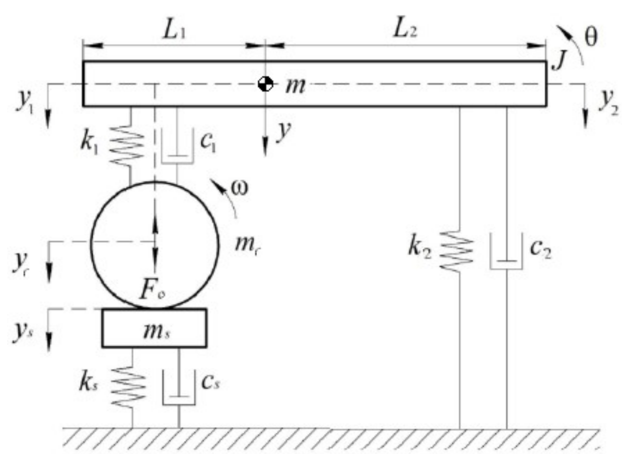


Fig. 5.36 The dynamic model for the simulation of tire compactors with a single vibrating roller (MRIETC 1)

The differential equations of motion of the dynamic model in the final form are:

$$(m_r + m_s)\ddot{y}_r + k_s y_r + k_1(y_r - y_1) + c_s\dot{y}_r + c_1(\dot{y}_r - \dot{y}_1) = (m_r + m_s)g + F_0 sin(\omega t), \quad (5.27)$$
$$m\ddot{y} + k_r(y_1 - y_r) + c_r(\dot{y}_1 - \dot{y}_r) + k_2 y_2 + c_2\dot{y}_2 = mg, \quad (5.28)$$
$$J\ddot{\theta} - k_2 y_2 L_2 - c_2\dot{y}_2 L_2 + k_1(y_1 - y_r)L_1 + c_1(\dot{y}_1 - \dot{y}_r)L_1 = 0, \quad (5.29)$$

where

$$y = \frac{L_1 y_1 + L_2 y_2}{L_1 + L_2}, \theta = \frac{y_1 - y_2}{L_1 + L_2}, F_0 = m_0 r \omega^2, \dot{y}_s = \dot{y}_r, y_s = y_r. \quad (5.30)$$

Figures 5.38-5.42 will present the results obtained during the simulation of different case scenarios (in the absence of damping in the considered system), aiming to highlight the influence of the parameters that define the roller-terrain interaction during the implementation of the imposed compaction technological task.

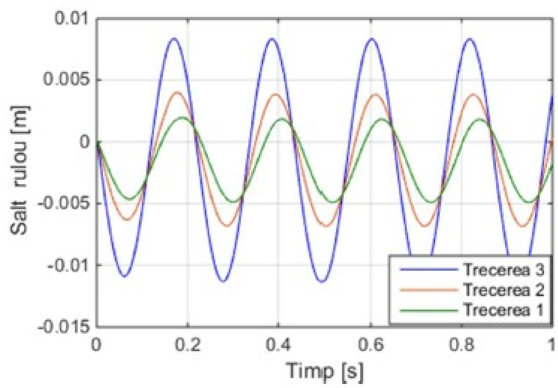


Fig. 5.38 Vertical roller movement at terrain contact after the first 3 passes (MRIETC 1)

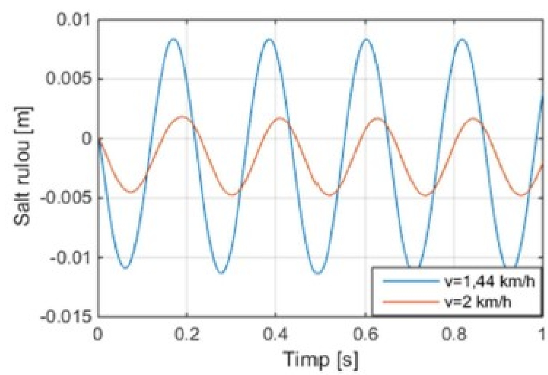


Fig. 5.39 The vertical movement of the roller when the speed of the machine is changed, on the first pass (MRIETC 1)

Based on the results obtained from the numerical simulation on the MRIETC 1 model, analyzing the graphs in figures 5.38 -5.42, the following can be concluded:

a) the parameters that in reality have a predictable evolution in time and implicitly according to the number of passes are defined in the model with the interparametric laws established in chapter 4 of the thesis (in terms of stiffness, settlement, degree of compaction, etc.) and thus it becomes possible establishing the behavior of the roller to the continuous evolution of the state of the terrain during the development of the technological process;
b) the evolution of the parameters that describe the performance of the technological process, after the first 3 passes of the compactor, are centralized in figure 5.42, being possible to analyze the efficiency of the technological process as a whole (with the continuous change of the state of the terrain, as well as of the working technology adopted – the increase or decrease in machine travel speed).

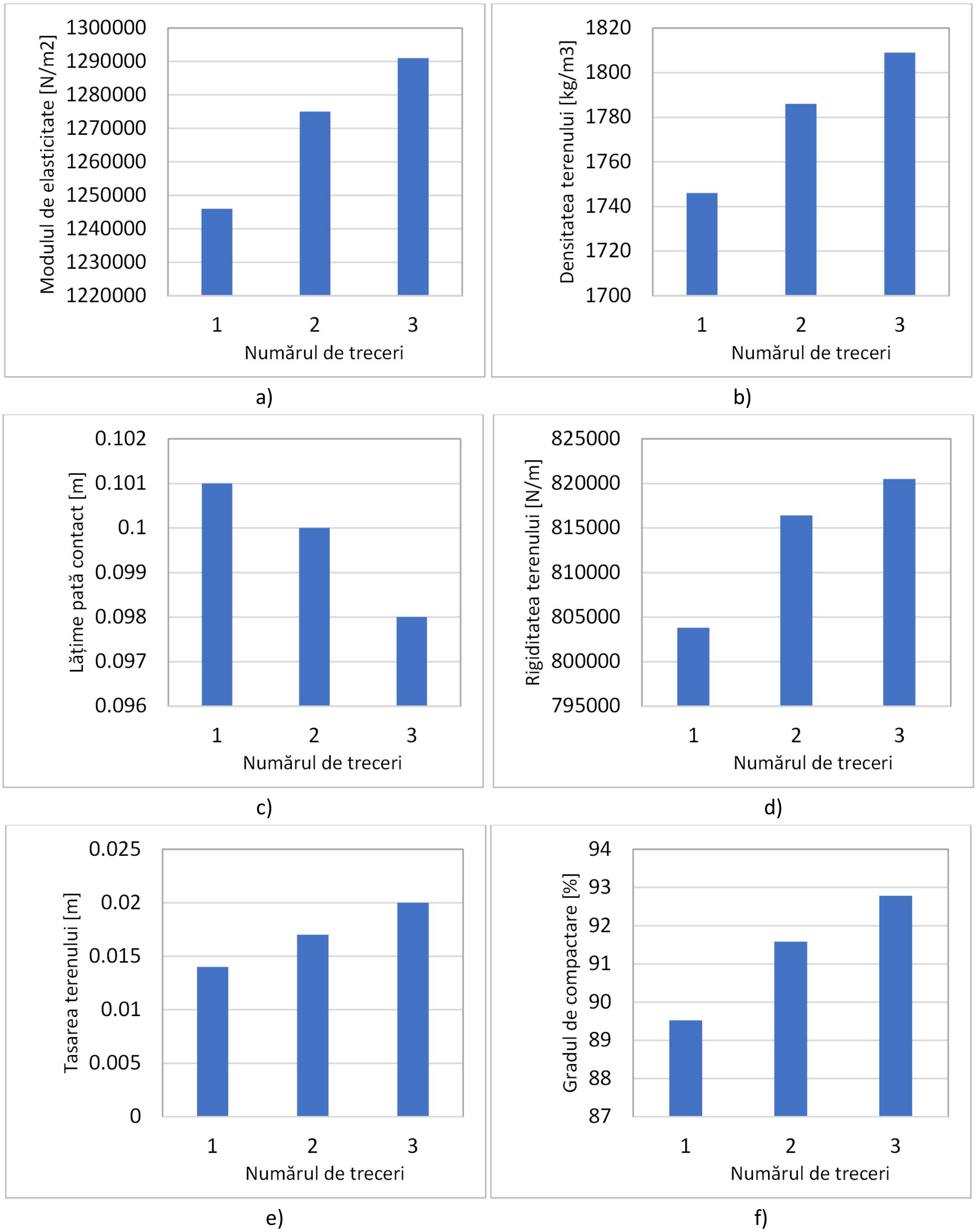


Fig. 5.42 Simulation of parameters with predictable evolution that define compaction process performance (MRIETC 1):
a) modulus of elasticity; b) density in dry state; c) the width of the roller-terrain contact patch; d) soil stiffness; e) terrain settlement; f) degree of compaction achieved after individual passes.

5.5.3. Modeling and simulation of single roller tire compactors (MRIETC 2)

If the MRIETC 1 model is simplified, if the overall approach to the movement of the compactor is not followed, but only in the direction of the vibratory drum movement [98 - 101], then the author of the thesis proposes the MRIETC 2 model presented in figure 5.43.

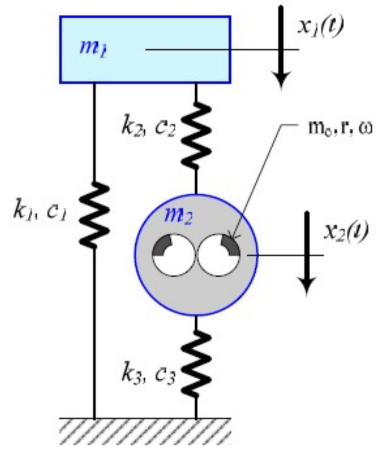


Fig. 5.43 The simplified dynamic model for the simulation of tire compactors with a single vibrating drum (MRIETC 2) [98]

The magnitudes of the system response have the results of the form

$$A_{10} = \frac{k_2 m_0 r \omega^2}{(k_1+k_2-m_1\omega^2)(k_2+k_3-m_2\omega^2)-k_2^2}, \tag{5.37}$$

$$A_{20} = \frac{(k_1+k_2-m_1\omega^2) m_0 r \omega^2}{(k_1+k_2-m_1\omega^2)(k_2+k_3-m_2\omega^2)-k_2^2}. \tag{5.38}$$

The number of cycles of vibration transmitted to the terrain by an active working tool of a compactor, when it passes over a monitored point can be estimated based on figure 5.44.

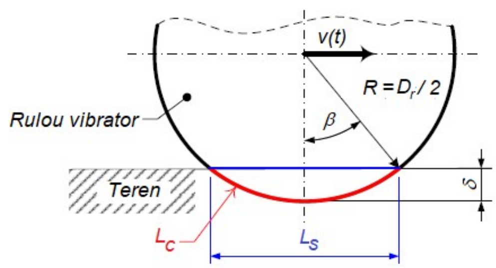


Fig. 5.44 Scheme for evaluating the number of cycles of vibration when passing the roller

$$L_c = D_r \beta = D_r arccos\left(\frac{D_r - 2\delta}{D_r}\right). \tag{5.42}$$

$$L_s = 2[\delta(D_r - \delta)]^{0,5}. \tag{5.43}$$

where D_r is the diameter of the drum and δ is the static deformation of the terrain. For any of the previous expressions, the number of cycles can be evaluated with the relation

$$n_{cycles} = f L_{\{c,s\}} v^{-1}, \tag{5.44}$$

where f is the frequency of the vibration generated by the vibrating drum and v is the speed of the equipment. Based on the relation (5.44), an analysis of the dependence between the number of cycles, the frequency of vibrations, the speed of the roller and the static deformation of the terrain was carried out. Adopted: D_r = 1.221 m, δ = 0.014 m, v = 1.34 km/h, f = 32 Hz and the ranges of variation δ = (0.008 - 0.020) m, v = (1 - 3) km /h, f = (20 - 34) Hz. This analysis was performed to justify that at a single pass, the local terrain consolidation is a sum of the partial deformations due to each cycle involved in the local process.

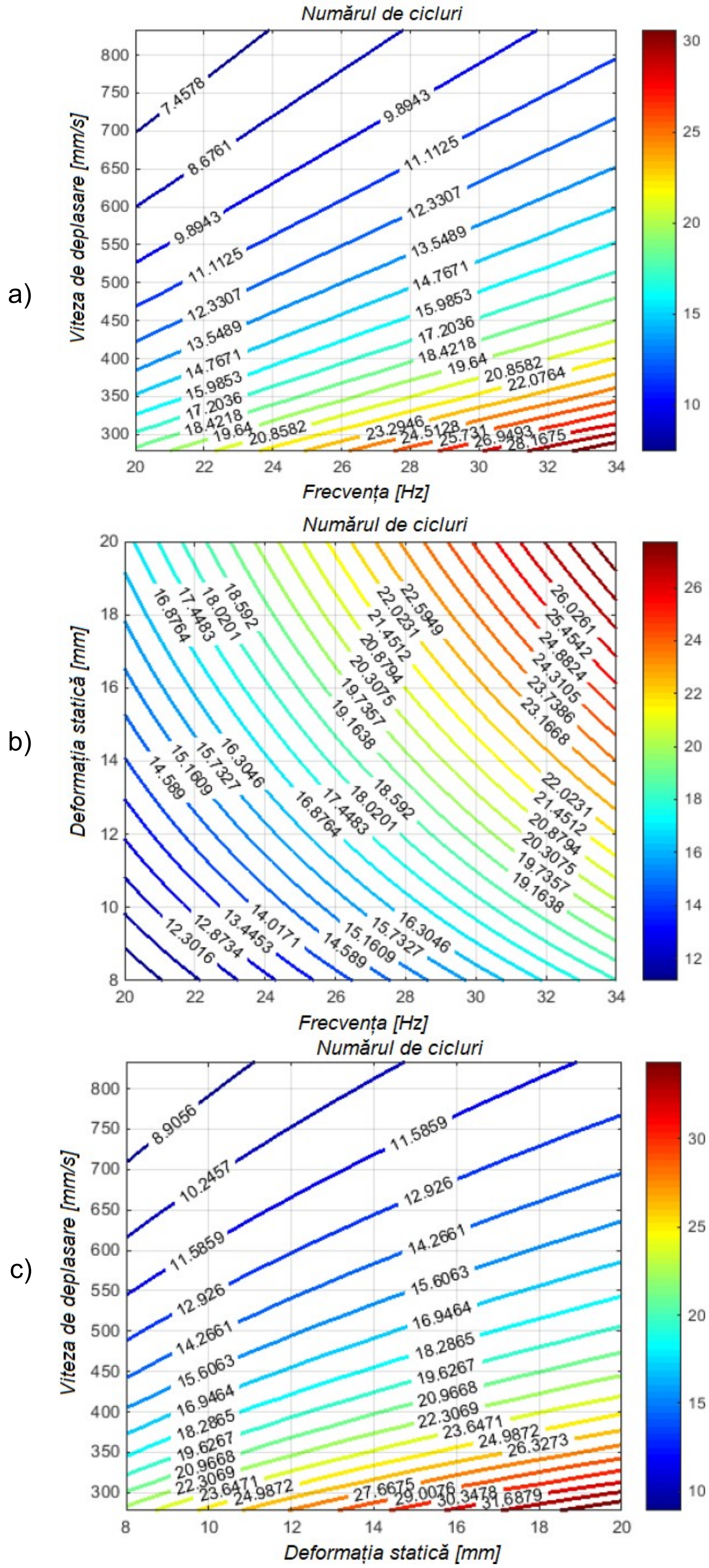
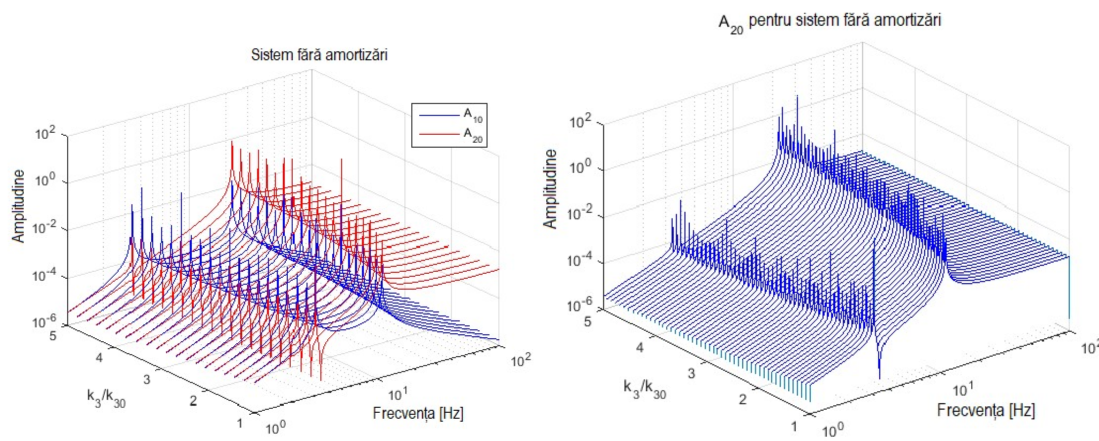


Fig. 5.45 The number of cycles in one pass of the vibratory drum, in relation to the speed of the machine and vibration frequency, for δ = 14 mm (a), at static terrain deformation and frequency, for *v* = 1.34 km/h (b) and, respectively, at machine speed and static terrain deformation, for *f* = 32 Hz (c). The number of cycles is marked on the isocline diagrams.

The analysis was performed under the assumption that the partial settlement of the terrain (in terms of stiffness ratio k_3/k_{30}) varies in a range of (1 - 5) and the dynamic response of the system in a range of (1 - 100) Hz. Evaluations were made for two case scenarios: with and without damping in the model. In this way, both the dynamic responses of both the chassis and the drum were simulated, but only for the roller the detailed analyzes will be presented. In the absence of damping, the diagrams in figure 5.46 show the spectral magnitudes of the amplification factors A_{10}, A_{20} - see relations (5.37) and (5.38).

Based on the diagrams in figure 5.46b, the displacement of the peaks of the relevant frequencies in relation to the increase in terrain stiffness was evaluated. On the other hand, when the presence of damping was taken into account, the spectral evolutions of the static deformation amplification factors, in terms of amplitude and phase, respectively, were evaluated and represented in figure 5.47.

The first two plots show both responses (chassis and drum), and the last two detail the vibration after the roller passes. The presence of damping is recommended if we compare the diagrams in figure 5.47 with those in figure 5.46. Thus, the first peak shows a strong decrease at full terrain consolidation, and becomes almost imperceptible with increasing ratio (k_3/k_{30}).



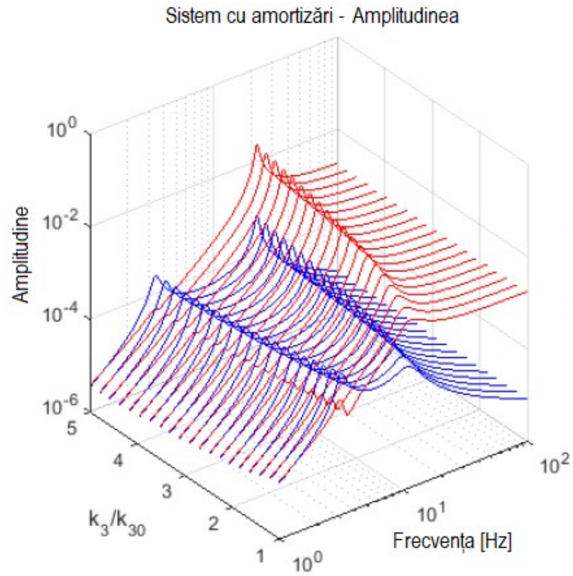
a) b)

Fig. 5.46 The evolution of the spectral magnitudines of the static deformation amplification factors, for the system without damping, depending on the terrain consolidation ratio (k_3/k_{30}) and vibration frequency: both responses (a) and only the drum response (b). In diagram (a), the blue line illustrates the chassis response and the red line illustrates the drum response.

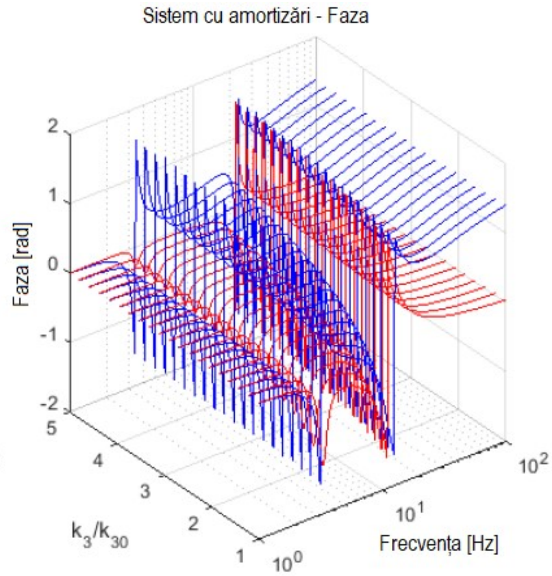
Comparative analysis of the simulated cases can be done more simply by using a overlapped graphics of the results indicating the displacement of the relevant frequency peaks in both situations. Taking into account the purpose of this study, the calculations were performed, both for the main values of the model parameters, and for some deviations of the reference values. Based on the experimental observations, a deviation of ±20% was considered for the ground stiffness and damping.

At the same time, it was assumed that the drum-chassis suspension parameters remain constant during a work cycle.

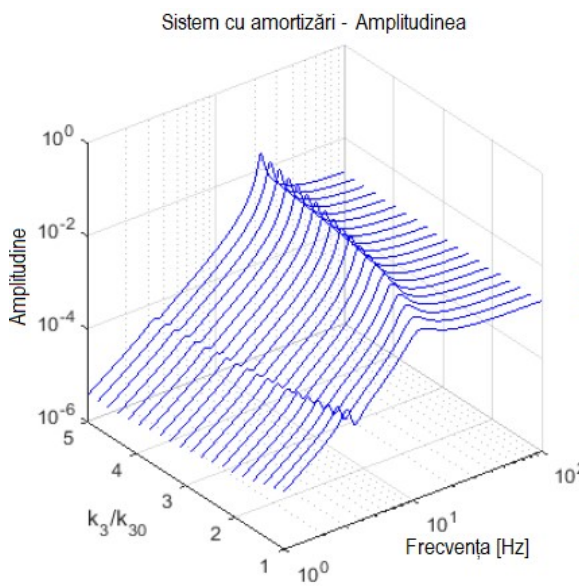
The results were presented in figure 5.48, along with two detailed views of the two areas that contain relevant developments for the displacement of the frequency peaks (k_3/k_{30}) and vibration frequency: both responses (a) and only drum response (b). In diagram (a), the blue line illustrates the chassis response and the red line illustrates the drum response.



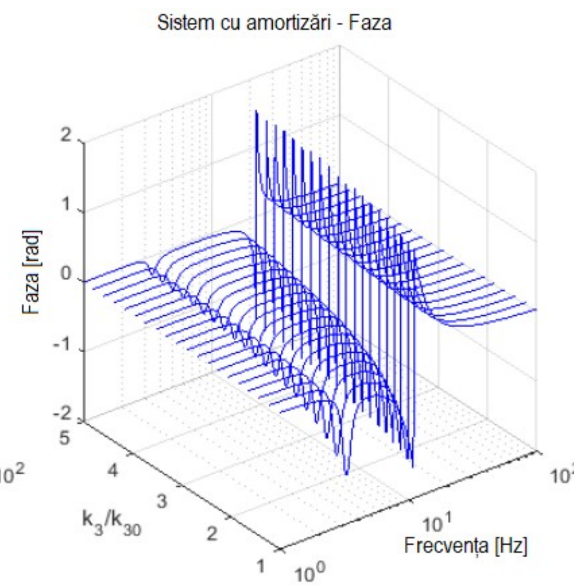
a)



b)

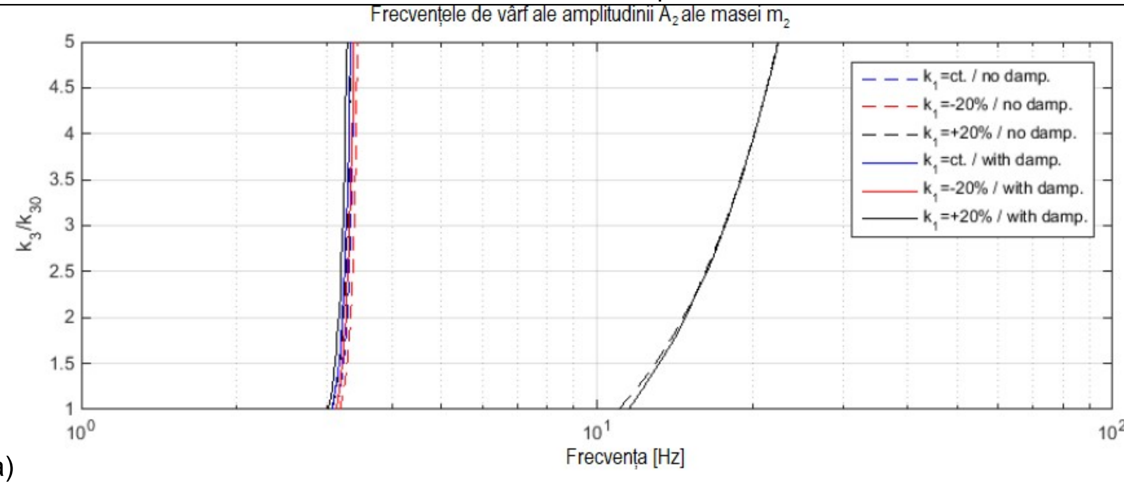


c)

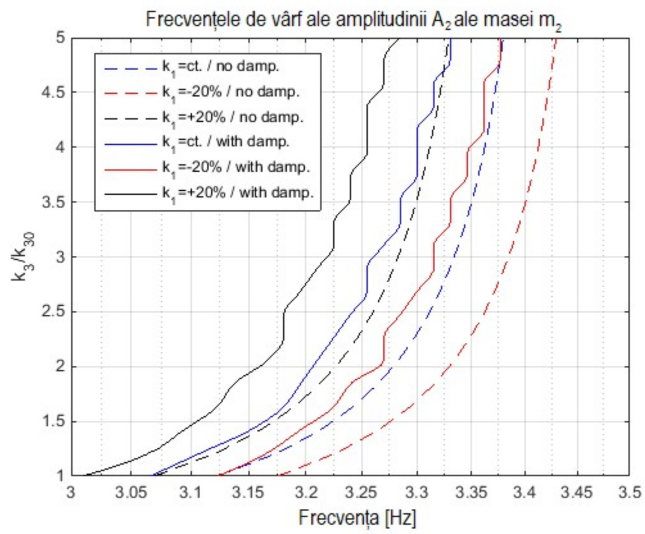


d)

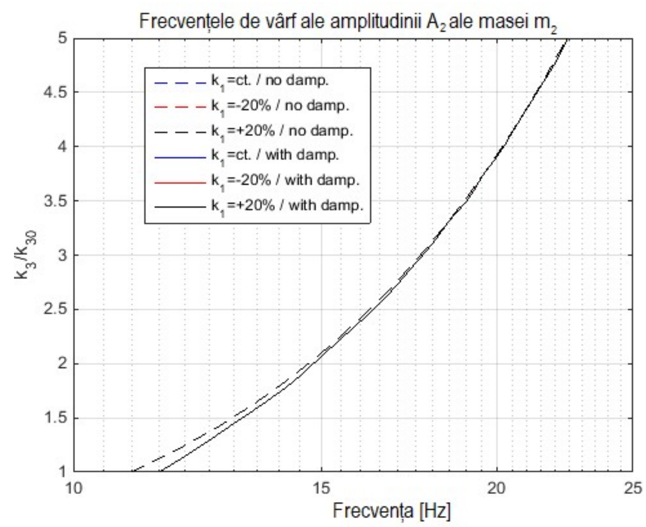
Fig. 5.47 Spectral evolutions of static strain amplification factors, for damped system, as a function of soil consolidation ratio (*k_3/k_{30}*) and vibration frequency: both responses, in terms of amplitude (a) and phase (b) and, respectively, the drum response, in terms of amplitude (c) and phase (d). In diagrams (a, b), the blue line indicates the chassis response and the red line indicates the drum response.



a)



b)



c)

Fig. 5.48 Comparative evolution of the frequency of the relevant peaks in the drum response, for the system with and without damping, as a function of the terrain consolidation ratio (k_3/k_{30}) and the vibration frequency: general view (a) and detailed with views of the relevant areas (b, c). A deviation of ±20% of the interaction parameters was assumed in terms of stiffness k_1 and damping c_1 (where applicable).

Analyzing the charts, the following conclusive observations emerge. The global view of the spectral plots does not show major changes in the peaks of the relevant frequencies (in terms of displacement in function by settlement). At the same time, on the enlarged images, two different behaviors are observed. Thus, the first peak (with a lower value) clearly shows a distinct evolution in relation to the increase in terrain consolidation. For the considered range of the ratio (k_3/k_{30}), the frequency changes by about 0.25 Hz, which is possible to verify in practice with real instrumental devices. Furthermore, it can be easily seen on the diagram in figure 5.48b that the differences become more relevant as the reinforcement ratio increases. On the other hand, the second peak (with high frequency) acquires approximately the same evolution, independent of the deviation from the reference value (see figure 5.48c). Differences appear only in cases without damping compared to the presence of damping. Additionally, it can be seen that the two curves become very close as the consolidation rate increases. These observations lead to a final conclusion that the first frequency peak is the parameter that must be monitored during the compaction process, in order to characterize the evolution/performance of the soil consolidation/settlement process.

5.5.4. Partial conclusions

Comparative analysis of the results obtained by simulation on the theoretical model of soil behavior (MTC) and on the rheological model of machine-terrain interaction (MRIETC 1), and the results of experimental investigations during the compaction process carried out in the soil channel (fig. 4.8 and Fig. 4.9) leads to the validation of these models, making them useful in the analysis of any compaction process carried out in concrete working conditions on the construction site.

The proposed rheological models of machine-terrain interaction (MRIETC 1, MRIETC 2) bring the following advantages:

- the appropriate connection between the two subsystems of the model (that of the terrain and that of the compaction machine) defined in the context of the assumptions and interparametric laws proposed in the previous sub-chapters of the doctoral thesis, allows:
  - ✓ correct estimation of the evolution of the terrain state during the compaction process;
  - ✓ the optimal choice of a compactor adapted to the specifics of the particular compaction work;
  - ✓ optimization of the working regime of the compactor;
  - ✓ establishing an optimal work technology;
- knowledge of the evolution of the stiffness coefficient *k* permanently correlated with the evolution of the terrain state Δh, offering the possibility of the optimal choice of the compaction machine, with the achievement of a predefined number of passes;
- the calculation algorithms that are the basis of the proposed MRIETC 1 and MRIETC 2 interaction models can be easily implemented in automatic systems for controlling the quality of the execution of soil compaction, with vibratory compactors ensuring the optimal correlation of the parameters of the work regime with the evolution of the state of the terrain, through following the increase of the stiffness coefficient *k*, either by increasing the settlement of the deposited layer Δh;
- the possibility of creating a technical database in the current context of the digitalization of technologies on road construction sites (*Industry 4.*0) in such a way that operators, installations and equipment involved in the technological process can communicate with each other directly via the Internet using access to platforms interconnected digital (to such technical databases) allowing the supervision of the entire process from design, production, logistics, commissioning, costs, etc.

6. Conclusions, personal contributions and general directions of research

6.1. Conclusions

The main contribution of the doctoral thesis is the development by the author of some models dedicated to the analysis of compaction performance by qualitatively evaluating the behavior of the roller-terrain interaction until reaching the required degree of compaction achieved after a predefined number of passes. The models contain in the calculation algorithm interparametric laws for defining the initial state of the analyzed material, making it possible to model their viscous, elastic and dissipative characteristics, completed with the modeling of the dynamic behavior of the structural and functional assembly of the vibratory roller compactor put into operation.

Each chapter of this doctoral thesis contains partial conclusions, and in this chapter only the main conclusions obtained in the two cases of approach: theoretical (analytical) and practical (experimental) will be highlighted.

In the first part of the doctoral thesis, a bibliographic synthesis of researches from the country and abroad in the field of compaction of construction materials with the help of vibrations is presented.

The research initiated within this doctoral thesis had as its starting point the need to develop and implement new models (by improving the existing ones) for the study of the behavior of weakly cohesive soils and some dynamic models to obtain information as close as possible to reality in what concerns the qualitative estimation of the specific parameters that define the performance of the vibratory compaction process of a terrain. Comparative analyzes were carried out between the behavior of the terrain during the static and dynamic operation of the compaction machine on physical, rheological, numerical and virtual models, with different degrees of freedom (from one-degree model to three-degree-of-freedom model freedom) for different types of weakly cohesive soils.

Thus, a technical database was created that is useful in the current context of digitalization of technologies on road construction sites (*Industry 4.0*), used for:

- establishing the required number of passes (adapted to the inhomogeneities of the terrain structure);
- choosing the appropriate compaction technology with a predetermined number of passes (thus avoiding overcompaction phenomena);
- knowing the values of the parameters ρ_d, E_{st}, k, Δh, D_i as the defining factors for evaluating the performance of the vibration compaction process of construction materials during putting in practice.

The consulted reports (provided by the ICECON S.A. Research Institute Bucharest) with the results of the series of experimental tests in laboratory and in situ conditions made it possible to parametrically assign the proposed models (being input sizes in the adopted models) so that they simulate as much as possible more faithfully the identifiable and measurable reality of the studied phenomena.

The evaluation of the level of performance of vibration compaction of weakly cohesive soils was the central objective pursued in the thesis and a particularly important aspect was placed on the identification of specific parameters that describe the evolution of the state of the soil under the action of the passes of the compactor, as parameters with predictable evolution in time and experimentally verifiable.

The design of the models was a parameterized one, thus being able to easily model different types of weakly cohesive soils, the thickness of the layers, the technology adopted (static or dynamic compaction), the number of passes, as well as the customization of each compaction machine put into operation.

Finally, the experimental and simulated results were validated.

6.2. Personal contributions

As a result of the research carried out both numerically through modeling and simulation, as well as experimentally within ICECON S.A. Bucharest may retain the following personal contributions:

a) analysis of the current state, both nationally and internationally, in the field of control of soils vibration compaction;
b) establishing the concept of an interactive model in the technological process of working with compactors (static or vibratory), through a qualitative estimation of the performance of the compaction process;
c) physical and mathematical modeling of the terrain subjected to static and dynamic actions (depending on the working regime adopted corresponding to the applied technology) for different compaction environments within the range of weakly cohesive soils;
d) the establishment of some interparametric laws (based on the initial geotechnical tests and the experimental ones carried out during the implementation of the exemplified compaction processes) which are the basis of the calculation algorithm of the theoretical model of weakly cohesive soils (MTC);
e) physical and mathematical modeling of the compactor-soil interaction in dynamic mode of operation, with a significant change in the stiffness coefficient of the soil and, respectively, when the vibration parameters are discretely variable, on the Voigt-Kelvin model;
f) highlighting the visco-elasto-plastic components, as a response of the terrain to the action of the compactor (with the qualitative estimation of the final settlement achieved), based on the specialized instrumental and computer systems Matlab/Simulink&SimMechanics (on MRTTC and EVP models);
g) the creation of a technical database for the optimization and customization of the proposed models, with an application role, taking into account the visco-elastic and dissipative characteristics of the analyzed media (poorly cohesive soils) and the dynamic behavior of the structural and functional assembly of the compactor put into operation;
h) evaluation of the dynamic response of the roller after successive passes over the layer, to characterize the performance of the compaction process, by knowing the parameters that define the evolution of the state of the terrain in terms of settlement, stiffness, modulus of elasticity, degree of compaction (on MRIETC 1 and MRIETC 2 models).

6.3. General directions of research

Continuing research in the future can be grouped into three directions:

- increasing the measurement accuracy of the parameters monitored during the compaction process by using the latest generation measurement instrumentation that ensures real-time recording of their variation;

- optimization of the proposed models using interparametric laws described by nonlinear functions of variation of the parameters involved in the compaction process;
- the design of a real-time automatic monitoring and control system of the essential parameters in the compaction process (by correlating the working regime of the machine with the physical-mechanical characteristics of the terrain after each pass) in order to execute at the maximum level of performance in terms of the number of passes, the equipment used, the technology applied and the degree of compaction achieved at the end. All this information obtained can be transferred to a technical database located on a digital platform to which all decision-makers involved in the execution of the respective work have access (in the context of the objectives of the currently implemented *Industry 4.0* concept).

List of published and presented papers

A. Publications in Web of Science journals

1. Bratu, P., Buraga, A., Chilari, O., Ciocodeiu, A.I., Oprea, I., *Evaluation of the linear viscoelastic force for a dynamic system (m, c, k) excited with a rotating force*, RJAV, Vol 16, No 1(2019), pp.39-46
2. Buraga, A., Debeleac, C., *Experimental Investigations and Numerical Simulations of Vibratory Compaction of Weakly Cohesive Soils*, RJAV, No 19(2022), Issue 2, pp.143-148

B. Publications in indexed volumes ISI Proceedings

1. Debeleac, C., Nastac, S., Buraga, A., *On Nonlinear Dynamics of Vibrating Compaction Process of Construction Materials*, Proc. of the 26th International Congress on Sound and Vibration, ICSV 2019, 2019, Montreal, Canada, 7 - 11 July 2019

C. Articles in BDI indexed journals

1. Debeleac, C., Nastac, S., Buraga, A., *Randomly aspects within the response of terrain due to characteristics uncertainty at vibrating compaction process*, Proc. of the 27th International Congress on Sound and Vibration - ICSV 27, 11-16 July 2021, 8p, SCOPUS
2. Debeleac, C., Buraga, A., Nastac, S., *Nonlinear analysis of the terrain layers response at vibrating compaction process*, Proc. of the 27th International Congress on Sound and Vibration - ICSV 27, 11-16 Jully, 2021, 8p, SCOPUS
3. Buraga, A., Debeleac, C., *A State-of-the-art Review of Compaction Control Tests Methods*, Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics - Hidraulica, nr. 4, pp. 42-50, 2022, EBSCO

D. Papers presented at scientific events and published in their volumes

1. Dobrescu, C., Braguta, E., Buraga, A., *Cercetări privind folosirea deşeurilor reciclabile pentru îmbunătăţirea capacităţii mecanice şi a stabilizării pământurilor argiloase*, în vol. Conferința tehnico-științifică internațională ”Problemele actuale ale urbanismului și amenajării teritoriului” ediția a X, p. 392-398, 27 noiembrie 2021, Chișinău, RM, ISBN 978-9975-87-779-4
2. Debeleac, C., Buraga, A. *Soluții tehnice și tehnologii ecologice utilizate pe șantierele de construcții*, în vol. Conferința tehnico-științifică internațională ”Problemele actuale ale urbanismului și amenajării teritoriului” ediția a IX, p.305-313, 16-17 nov. 2018, Chișinău, RM
3. Bejan, S., Buraga, A. *Compactarea pământurilor coezive și slab coezive, modele dinamice pentru studiul interacțiunii rulou-teren*, în vol. Conf. tehnico-științifică internațională ”Problemele actuale ale urbanismului și amenajării teritoriului” ediția a IX, p.256-264, 16-17 noiembrie 2018, Chișinău, RM, ISBN 978-9975-87-384-0

E. Papers presented at scientific events

1. Debeleac, C., Buraga, A., *Field evaluation of compaction degree using internet-of-things*, The 9th International Conference on Advanced Composite Materials Engineering, COMAT 2022, 17-18 October 2022, Univ. Transilvania Brasov, Romania.
2. Debeleac, C., Buraga, A., *Behavior model of weakly cohesive soils in the static compaction process*, The 18th International Conference of Constructive Design and Technological Optimization in Machine Building Field, OPROTEH 2023, May 11-13, 2023
3. Buraga, A., *Evaluation of the action of the roller on weakly cohesive soils in the static compaction process,* 18th International Conference of Constructive Design and Technological Optimisation in Machine Building Field, OPROTEH 2023, Bacău, May 11-13, 2023
4. Buraga, A., Debeleac, C., *Computational method for road layers compaction degree identification*, The 9th International Conference on Computational Mechanics and Virtual Engineering COMEC 2021, 21-23 October 2021, Univ. Transilvania Brasov, Romania, Poster
5. Buraga, A., Debeleac, C., *Compaction quality inspection method of soil embankment based on compaction control system*, 9th Internat. Conference on Computational Mechanics and Virtual Engineering COMEC 2021, 21-23 Oct. 2021, Univ. Transilvania Brasov, RO, Poster
6. Buraga, A., Debeleac, C., Nastac, S. *In Field Testing of Vibratory Compaction Performance Level for Construction Materials*, eMECH 2020&COMAT 2020, Brasov, Romania, Poster

F. Awards

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