"Dunarea de Jos" University in Galati
Doctoral School of Engineering

DOCTORAL THESIS

SUMMARY

THE DYNAMIC COMPACTION THROUGH VIBRATION OF ROAD STRUCTURES FROM STABILIZED SOIL WITH ORGANIC BINDERS

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INTRODUCTION

As a rule, the Earth, as basic material of a building, or as actual building material, hasn't the ideal form from the point of view of the engineer in the field. It is known, that this problem is exceeded through different specifically procedures of improvement of soil's quality, one of the most important and frequent actions on the soil being the densification achieved by compaction.

Very often used for the densification of the soil, the dynamical compaction has long been applied to different types of soil, but this work deals with vibrating dynamic compaction of land-based structures stabilized with ecological binders. The surface compacting of non-coating soil can be performed very efficiently with vibrating rollers, these being compacting equipments with smooth cylinders equipped with a vibrating mechanism.

The method through which is specified and checked the compaction level depends by the nature of compacted element and it is very important for obtaining of desired properties for used material, especially if a relatively uniform result of the compaction process is pursued. A high level of quality also requires proper control over the entire compacted surface, which can be achieved economically through an integrated continuous compaction control system.

Thus, one of the factors that significantly affect the properties of an earth, and consequently the compaction process of the earth, is the water content which is often considerably outside the builder's possibilities of influence. As the water content inevitably varies either due to the atmospheric changes or the extent of the surface on which it is being worked, it is important to determine the implications of this phenomenon on the method of controlling of the compaction result.

This Doctorate thesis has as goal the instrumental and informative appreciation of the structural and functional laws that lead the interaction between the vibrating equipment and the compacted material with the purpose of formulating of a set of applicative models that allow us to provide the interface of technological equipment - process and with monitoring and controlling of the functional parameters and with their keeping in the optimal work area.

Taking into account the necessity and opportunity of this doctorate thesis, during the all investigations the following main objectives have been pursued, and namely:

- the multi-criteria evaluation of the current level of investigation in the field based on a critical examination of relevant achievements both at national and international levels;
- the comparative investigation of behavior in static regime, but especially in the dynamic regime of rheological models, in order to identify and highlight the specific features concerning their ability to simulate the phenomenological intimacy (depth) of the interaction working object - processed material;
- the determination of the set of rheological elements that will constitute the theoretical basis for developing and grounding of the final models, with an applicative role, taking into account the elastic and dissipative characteristics of the analyzed media and the considered dynamic behavior of the structural and functional ensemble;
- the creation of a set of "in-situ" instrumental tests supplemented with a range of experimental laboratory tests executed on a base of multi-core systemic analysis plan, for guarantee of the database for the behavioral harmonization process and the parametric assignment of the mathematical/numerical models with identifiable and measurable reality;
- the theoretical combination of the set of interface models, by structural creation and functional correlation of the inertial, conservative and dissipative elements with verification, in order to optimize the following essential parameters: the structural complex versus the simplicity fidelity, the level of detail versus the availability of solving;
- the determination of the final configuration, conferring of the working characteristics and confirmation of the set of interface models with the evaluation of the obtained level of performance.

The Doctorate Thesis is structured in 6 Chapters, developed in 108 pages, containing 55 images, 19 tables and 130 bibliography references.

Further, will be presented a short description of the content of Chapters of this Thesis.

Chapter 1 contains this stage of investigation concerning the level of knowledge and of currently studies in the field of compaction of road leyers (constituted from stabilized earth, asphalt mix). Also, the general notions of dynamical compaction, rheological modeling and the objectives of doctorate thesis are presented.

In **Chapter 2** there are presented the constructive, functional and technological parametric requirements of the working objects of the compactors, taking into account and emphasizing those that use the vibrations in the technological process of compacting of the stabilized lands. Similarly, it is argued on theoretical and practical reasons the importance of the correlation between the technological solution, the nature of the land and the compaction equipment used so as to reach a certain level of performance imposed on the execution of the specific works of road structures.

Chapter 3 includes a wide range of dynamic models used to simulate vibratory compactors, being presented in order of their constitutive complexity. The dynamic analysis of vibration-field soil interaction for earth, as well as comparative analysis methods of the vibration compacting process, the E-V system response to dynamic inertial harmonic excitations. The vibratory movement of the vibratory-field assembly, the combined vertical and rotation translation vibration around the horizontal transverse axis. For these dynamic models, the differential motion equations were performed, showing the instantaneous displacements of the compaction masses or points of interest (modeled as a rigid). The dependence of the field compaction on the static modulus of linear deformation, the strength of force, the stiffness coefficient, as well as the axial compaction force of the ground are determined. Finally, based on these laws, the global dependence of all the previously exposed parameters that have direct implication in the compactor-field interaction process was determined.

In Chapter 4 are analyzed and deduced the functional laws between the characteristic parameters of the lands determined on the basis of the experimental determinations. The dependence of dry soil density on the static linear deformation modulus, the optimal thickness, the width of the contact surface between the roller and the ground, as well as the compaction of the layer of the road system, was firstly established. Also, the dependence of the field compaction on the static modulus of linear deformation, the stiffness coefficient, the resistance force, as well as the axial compaction force of the ground, has been established. Based on these laws, the global dependency of all previously examined parameters that has direct implication in the compactor-field interaction process has been established.

In **Chapter 5** is described the methodology and the plan of achievement of experimental tests for technology validation in the case of compaction of stabilized soils, mentioning the used experimental methods, as well as the specifically equipment of monitoring of essential parameters of compaction process. Experimental tests were performed on lands of fillings within the Testing Polygon). Thus, the physical and mechanical parameters of the terrain (humidity, compaction degree, density, plastic compaction, longitudinal elasticity modulus, Poisson coefficient, volume elastic modulus, CBR caliber index, determination of monoaxial compressive strength on stabilized earth samples) have been determined after successive passes, as well as the frequency spectrum of vibrations during the process of compaction. The necessity to evaluate these parameters is because some of them represent input sizes in the dynamic model of the compactor-terrain interaction proposed in this thesis.

The Chapter 6 comprises final conclusions, personal contributions in the field of thesis and future directions of investigation.

CHAPTER I

ACTUAL STUDY OF THE RESEARCHS. OBJECTIVES THESIS

1.1 Introduction

According to earthworks of stabilized road structures and natural land used for filling, can be defined by the following factors: porosity, humidity, compactness. At certain values of the factors that render the state of the earth, there is a certain behavior of the land to the action of external forces applied through static or dynamic mechanical means.

In its composition, the earth has solid mineral particles, designed by chemical or physical degradation of rocks, which may contain or may not contain the organic matter. So, the following three phases can be mentioned:

- solid phase consisting of the mineral skeleton;
- the liquid phase (in water) which completely or partially fills the voids between the granules;
- the gaseous phase (air) that fills the voids unoccupied by the liquid phase. [14] ***

It is possible in some cases that one of the last two phases is missing. When the liquid phase is missing, the soil is considered dry, and when the voids between the granules are filled with water, the soil is considered saturated. Depending on the proportion of the three phases (solid, liquid and gaseous), in the composition of a soil, the size of the granules, the combination of component elements, result different types of soils as well as their their physico-mechanical characteristics. [14] ***

1.2. General concepts of dynamic compaction

The compaction term is considered depending on the proportion of volumes or masses between the air content, the water content and the solid part of the soil. In this way, the degree of compaction is controlled by dry soil density, which shows the mass of the solid part in the volume unit of the compacted material. In figure 1.1. are presented in the form of a diagram the solid, liquid and air phases of a compacted material.

In the Annex A are presented the definitions of some terms considered in the compacting phenomenon, as well as the relations of connection between them.

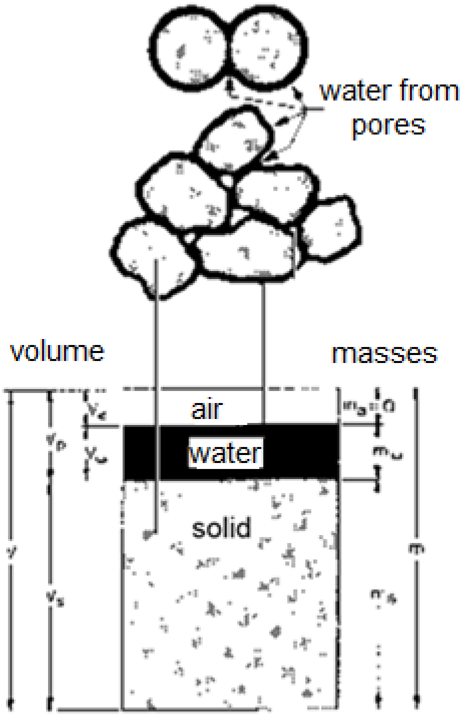


Figure 1.1. Soil composition

In order to appreciate the effect of a dynamic load on granular material under pressure, were conducted various laboratory studies in two ways, through using the controlled cyclic vertical pressure, respectively by using the controlled cyclic vertical acceleration shown in Figure 1.2. [2; 3, 33]

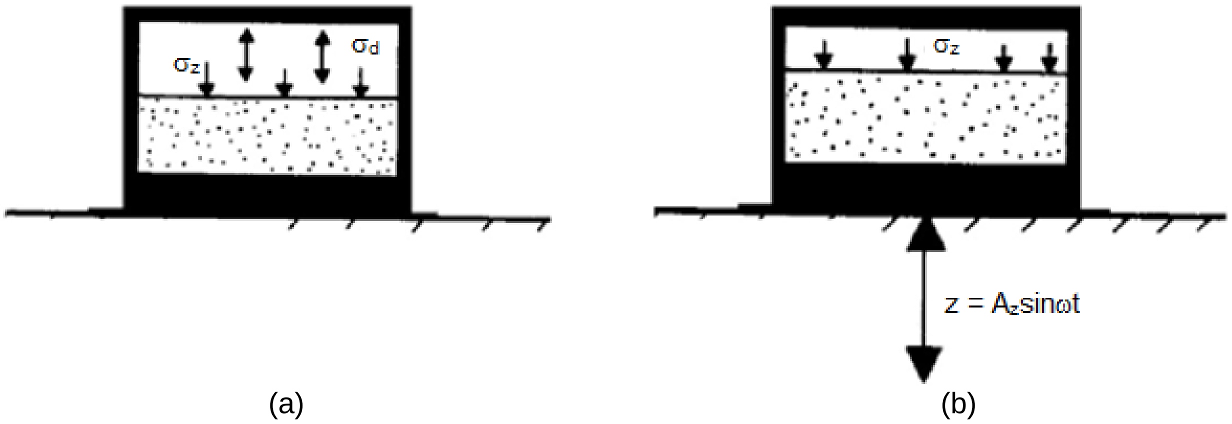


Figure 1.2. Dynamic compaction of a granular material: [33]
(a) cyclic vertical pressure;
(b) vertical accelerations cyclical.

The tests have shown that even in the case of null ambient pressure $\sigma_{z(1)} = 0$, the decrease in porosity does not occur before reaching an acceleration peak equal to the gravitational acceleration. At the same time, it is noticed that with the increase of the surrounding pressure, the magnitude of the acceleration peak at which porosity begins to decrease is increasing. [4]

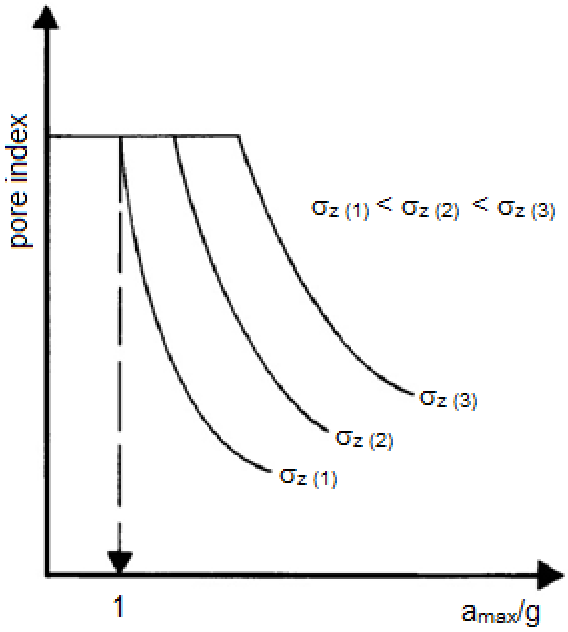
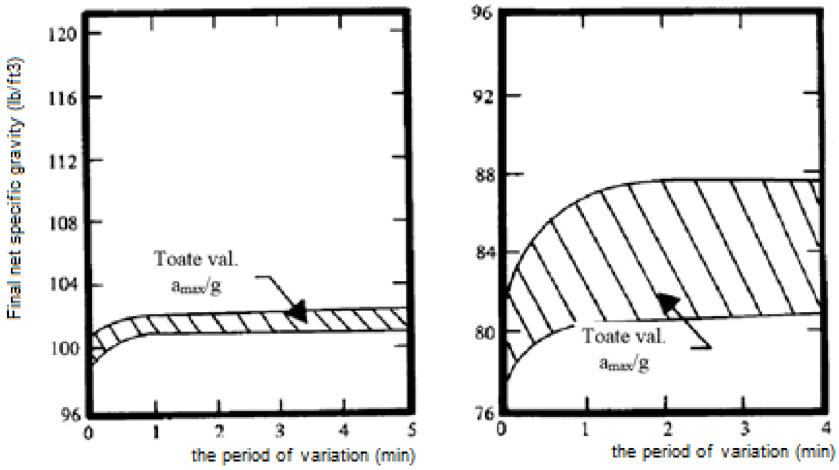


Figure 1.3. Variation of the porosity of a dry sand during the tests compression with vertical cyclic acceleration

In the figure 1.4. is presented the net specific weight variation in relation to the vibration period for both dry sand and wet sand, both of them being subjected to a vertical cyclical acceleration.

Referring to the Figure 1.4. the same can be noticed that, compared to dry sands, wet sands have a wider final weight distribution of final net weight. What it means that in case of compaction of wet sands, in addition to the magnitude of the cyclical acceleration, here are other parametric with an important influence of the given phenomenon.

Therefore, the development of specific cyclic deformations caused by oscillations of the vibratory cylinder, is considered to be the one that provides the best reporting of compaction produced with this machine. The experiments have demonstrated that this mechanism is present in the dynamic compaction of all samples of granular materials, both cohesive and non-cohesive.



(a) (b)

Figure 1.4. The influence of the vibration period in dynamic compaction [33]
(a) dry sands
(b) wet sands

1.3. Rheological modeling in the process of mechanical compaction of the soils

Modeling and simulating the behavior of the soil, under the action of external tasks, depends on the knowledge of the modern rheology development trends complemented by some current achievements, as well as the difficulties that appear in the establishment of laws on mechanical soil governance. [46]

Taking into consideration the theoretical studies to determine the laws of mechanical behavior of the earth, we distinguish the following rheological models: [46]

a) Micro-rheological models
b) Phenomenological models

1.4. Current state in the compaction field through vibration

Thus, soil parameters such as initial dry density, granulometric distribution, particle form and water content are the most important factors that give us information on the efficiency of the compaction process. Therefore, the different soil types have various compaction curves, as can be observed in Figure 1.9.

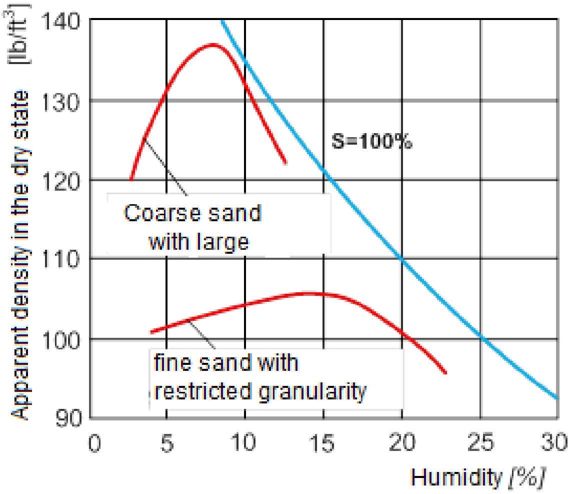


Figure 1.9. The compaction curves for different ground types
depending on humidity [15]

According to Santamarina [24], which argues that the movement of particles in a horizontal direction is diminished faster than the vertical direction, as shown in Figure 1.11.

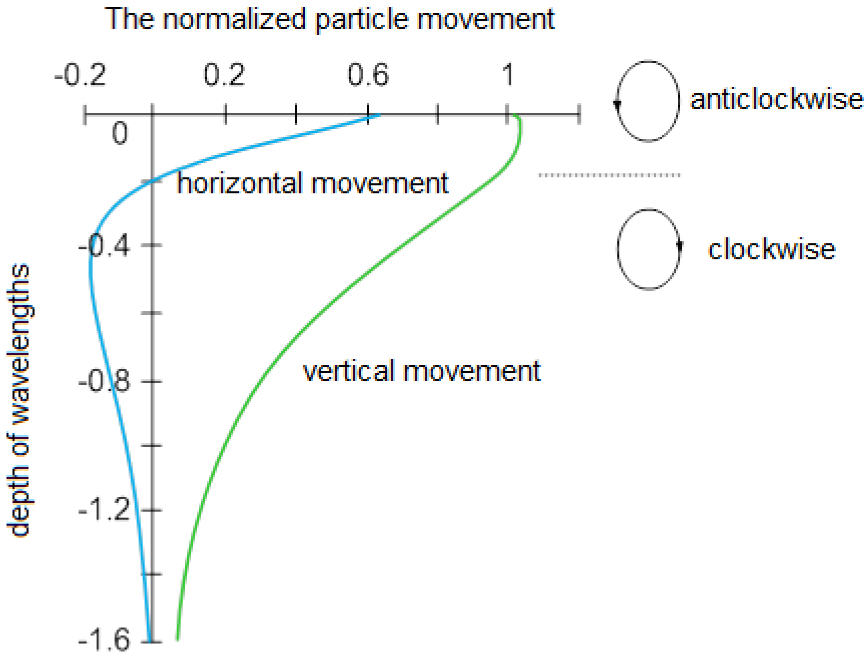


Figure 1.11. Movement in the horizontal and vertical direction of the particles function of depth [24, 46]. On both axes, the dimensions are in meters.

In the figure 1.12. is demonstrated how the dynamic compaction component is used for macro-granular materials and helps to increase the density in the dry state of the soil in terms of dynamic compaction. All of these are generated by the rotation of some eccentric masses being mounted inside the roller.

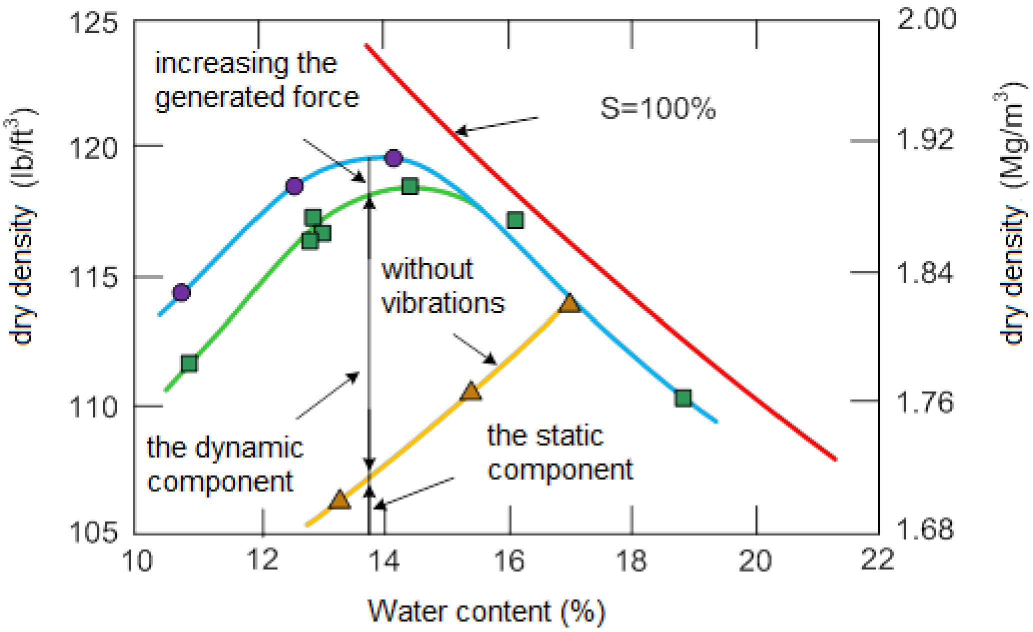


Figure 1.12. The Soil compaction curves compacted with and without dynamic effect [16, 17, 44, 46].

1.5. Modeling on non-cohesive soils of vertical dynamic loading

When shaping the earth, is taken into account that there are elasto-plastic effects in the contact area between the cylinder and the soil, thus to the depth is developing the elastic behavior [25]. Using the overlapping effect process, the soil is considered to be composed of two substructures, the plastic and elastic areas, modeled separately. At the end, the results are superimposed, fulfilling the compatibility conditions.

The semi-space is idealized by a semi-elastic semi-infinite of height ζ_0, but the contact surface between the soil and the cylinder is considered as a rigid base without a mass, of area A_0 (Figure 1.13.).

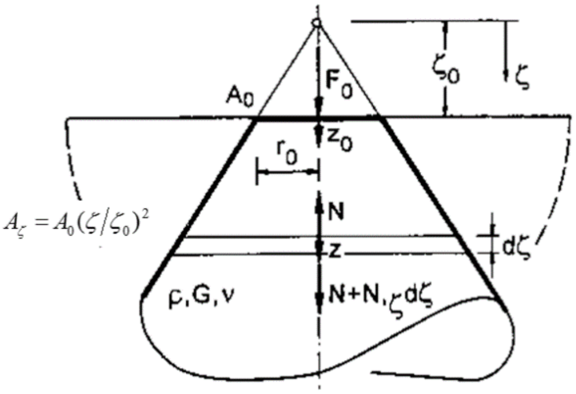


Figure 1.13. The model of the semi-infinite elastic cone

The dimensions of the loading surface correspond to the dimensions of the rectangular area considered (a = a_0, b = b_0 and that A = A_0), but, due to the necessary balance at the soil level, the contact force is equal to the elastic force of interaction (F = F_0). The total elasto-plastic displacement of the cylinder z_d consists of elastic deformations z_0 and plastic z_p of the soil figure 1.14.

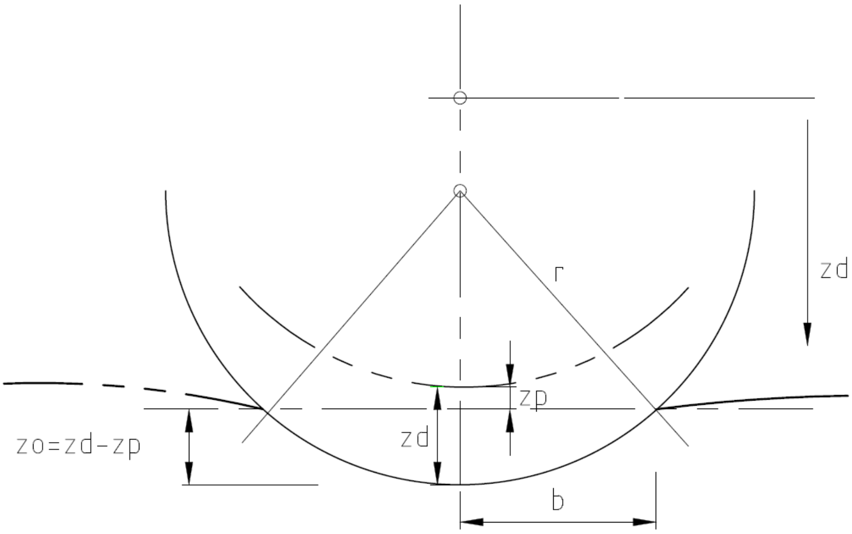


Figure 1.14. Elasto-plastic soil deformation non-cohesive under the impact of the cylinder

The relationship between the contact force and the plastic deformation is achieved through using the formula given by the theory of bearing capacity of foundations on the ground. Thus, the carrying capacity is:

$$N_B = A\sigma_B \tag{1.2}$$

In which $A = 4ab$ is the area of the loading surface, but

$$\sigma_B = cN_c s_c + \gamma_o t N_q s_q + \gamma 2bN_\gamma s_\gamma \tag{1.3}$$

is the compressive tension of the field given by Prandtl-Buisman formula,
where (*c* - soil cohesion,

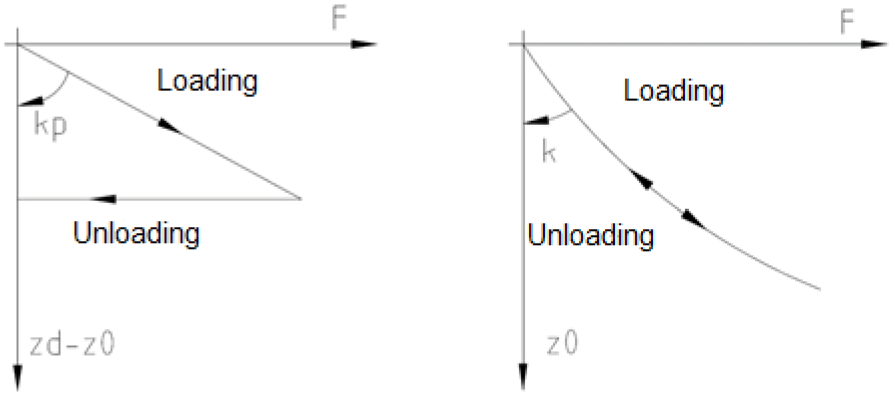
γ - the specific soil weight,

γ_0 - specific weight of the side filling (if any),

t - the thickness of the filling
N_c, N_q și N_γ - load capacity factors,
s_c, s_q și s_γ shape coefficients).

From this expression, we observe that the plastic balance develops as a linear force-displacement. Because the elastic effects occur in the soil only during the discharge (lifting of the cylinder), the relation 1.7 is valid only for the loading phase (Figure 1.15.a).

In the Figure 1.16 is shown the elasto-plastic behavior of the soil loaded by the vibratory cylinder. According to the presented theory, the plastic deformations are linear (relation 1.7).



(a) (b)

Figure 1.15. The force - displacement relationship in case ideal plastic behavior (a) and elastic ideal (b)

The compacted material, with both substructures considered in its shaping, and the dynamically excited cylinder of the vibrating cylinder, are overlapping under the conditions of compatibility. Taking into consideration that no stretches can occur between the soil and the cylinder, must be considered the loss of contact.

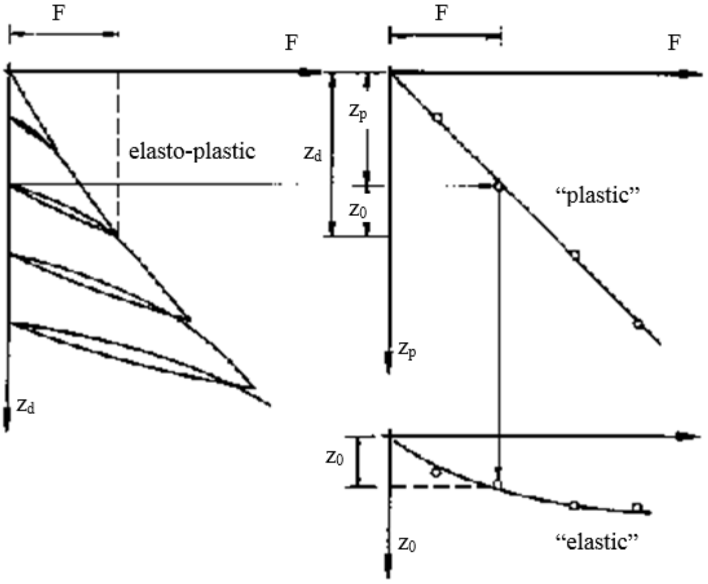


Figure 1.16. Establishing punctual deformations plastic and elastic properties of the soil

Thus, the general form of the connection relationship between the cutting voltage and specific deformation, which occurs in the case of dynamic request, represented in the figure 1.17. A load cycle is defined as starting and ending at a same point by a maximum cutting voltage. A loop, represented by a full voltage return, is described through the two ***G*** and ***D*** parameters.

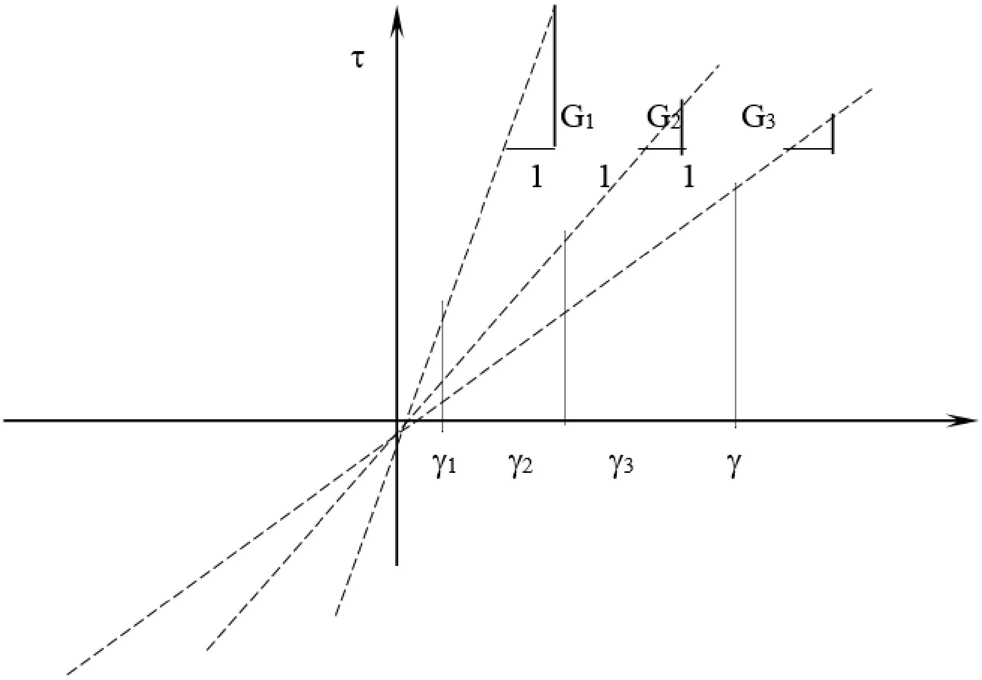


Figure 1.17. The cutting tension - specific deformation relationship for dynamic solicitation

1.6. Opportunity and the objectives of the doctoral thesis

Thus, according to the opportunity analysis as well as the requirements underpinning the need for such research, **the purpose** of this doctoral thesis should emphasize the following:

- *instrumental and informational appreciation of structural and functional laws which leads to the interaction between the vibrating equipment and the compacted material;*
- *checking the functional parameters and keeping them in the optimal area;*
- *instrumental and informational monitoring.*

Taking into consideration the necessity and opportunity of this doctoral thesis, the following **main objectives** are set:

- assessing the current level of research in the field;
- establishing the rheological models that present the theoretical basis for the progress and substantiate the elastic features, dissipative and dynamic of the structural and functional assembly between land- equipment;
- indication of interface models, through the structural creation and functional correlation of the inertial elements, conservative and dissipative, in order to optimize the compaction process;
- the static and dynamic behavior of the rheological models in order to identify and highlight the elements of the specificity of the working organ interaction and processed material;
- characteristic correlations of laboratory value sizes and in the field „in situ” for mineral aggregates, natural and ecologically stabilized soil;

CHAPTER II

Parametric requirements of compaction technology of the stabilized earth

2.1 Generalities

Compaction is a process of earthling (or any other filler material), as a result of the use of technological equipment. In this way, by successive application of the compressive forces or dynamic loads on the foundation ground or of the layers put into operation in earthworks, which aim to redistribute solid particles with the removal as much as possible of air and water from the internal structure of the land. [46]

The objectives of land compaction are:

a) in the case of land:
  - increasing the density and load-bearing capacity of road layers;
  - decreasing of compressibility and permeability.

b) in the case of asphalt mixtures:
- increasing of density;
- increasing of stability;
- increasing of wear resistance.

Depending on the way the compaction load is applied over the analyzed area, some compaction methods are different:

- static (by roller);
- dynamic (through vibration, impact, kneading).

In the Figure 2.1. there is a wide range of compacting machines that do not use vibrations in the working process.

Figure 2.1. Examples of machines that perform static compaction on the ground

According to the analysis of the technical characteristics of vibratory compactors produced both in the country and internationally, we distinguish some constructive classes, mainly according to the working technology and the nature of the land, in this way: [46]

a) trailed vibratory compactors;
b) self-propelled vibratory vibrators, with one-piece chassis and two smooth rolls. The vibration is done with either a single roll or both rolls but the traction is carried out with either one roll or total, on both rolls;
c) self-propelled vibratory compactors with two profiled rolls with articulated chassis. Thus, the vibration is performed on both rolls or only on one, and the traction is performed on both rolls
d) self-propelled vibratory rollers with two smooth rolls and articulated chassis. Vibration is done with either a single roll or both rolls, and the traction is performed on a single roll or on both rolls;
e) Mixed self-propelled vibratory compactors with articulated chassis. The vibration is

performed with a front roller, and the traction is carried out on two or four tires placed in the rear. Total traction systems are also used simultaneously on roller and tire.

2.2 Model with single degree of freedom for vibratory roller

The vibrating system with rotating forces consists of the roller shaft, which are located symmetrically to the median plane and in eccentric mass phase, bearing in the side flanges of the roller and the drive system.

The vibration system with one-way force is applied in two constructive variants, namely: with inertial vibrator with two eccentric masses mounted in the phase, cinematic synchronized, and with a pendulum vibrator mounted on the roller shaft.

For displacement, usually, are used hydrostatic systems with closed circuit, which offers the following advantages:
- slow and progressive command in both displacement directions (forward/ backward)
- the possibility of increasing the pump speed with favorable implications for the lower amount of circulating oil;
- braking with no circuit losses;
- more economic dimensioning of the power circuit pipes.

With the help of *self-propelled compactors with a single vibrator roll* we can compact a wide range of earth. Some of the most representative examples of vibratory rolls are shown in the Figure 2.2.

a) b)

Figure 2.2. Compaction equipment with single degree of freedom for vibratory roller:[1]***
a) smooth vibrating roller; b) profiled vibrating roller (with crampons).

2.3 Model with double degree of freedom for vibratory roller

The tandem vibratory roller compactors represented in the Figure 2.3. being widely used in all types of works and particular in the implementation of asphalt mixtures, where it produces a high productivity and a good quality of the performed work. [46]

a) b) c) d)

Figure 2.3. Compaction equipment with double degree of freedom for vibratory roller
a) model Catterpillar; b) model Bomag; c) model Hamm; d) model Ammann. [1, 2, 3, 4]***

Thus, the constructive solutions are correlated to the state of the art technology and are characterized by: [44, 46]

- hydrostatic integral transmission, in closed circuit, with variable speed continuously;
- hydrostatic driven vibrations in closed circuit, full-back, with three-pitch amplitude and two frequency steps;
- automatic control of frequency, displacement speed, vibration control and of the compaction effect (as an example, the intelligent monitoring system of the degree of compaction Variocontrol, the compaction process management system ,Asphalt Manager”, with real-time control and GPS positioning, applications of Bomag Company)
- articulated chassis, front and back full hydrostatic steering;
- equipment and auxiliary facilities: front double-roll (composed of two semi-trailers), equipped with rotary control, with edge-cutting device and with displacement in a transverse direction on the main machine axis. [46]

Vibro-generators designed and built by the company Hamm generate horizontal oscillations, which determines an altitude of the acceleration diagram in Figure 2.4, greatly improving the compacting effect shown in Figure 2.5, compared to the vibration case [27, 46].

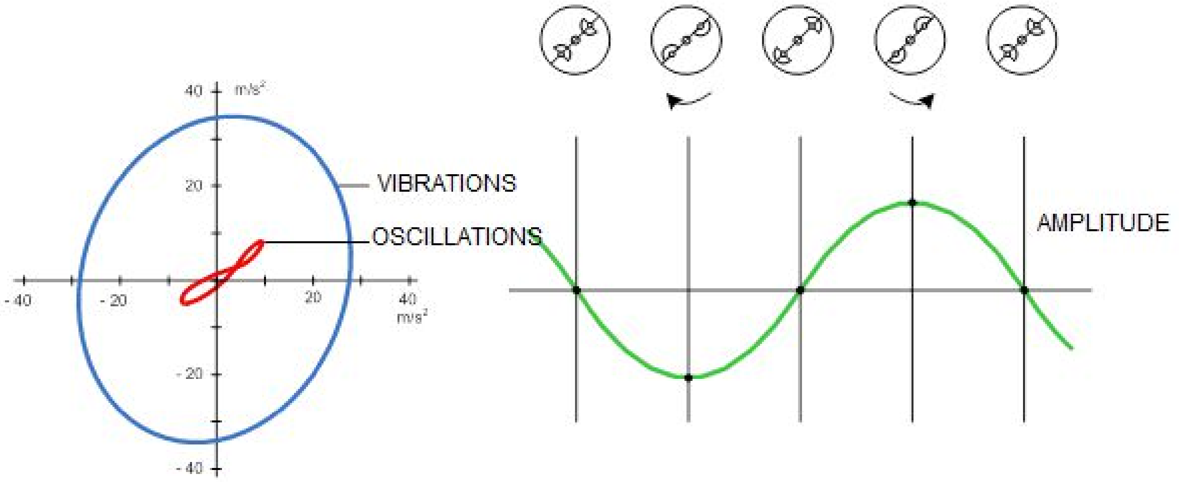


Figure 2.4. Oscillations produced by the company's vibro-generators Hamm [27]

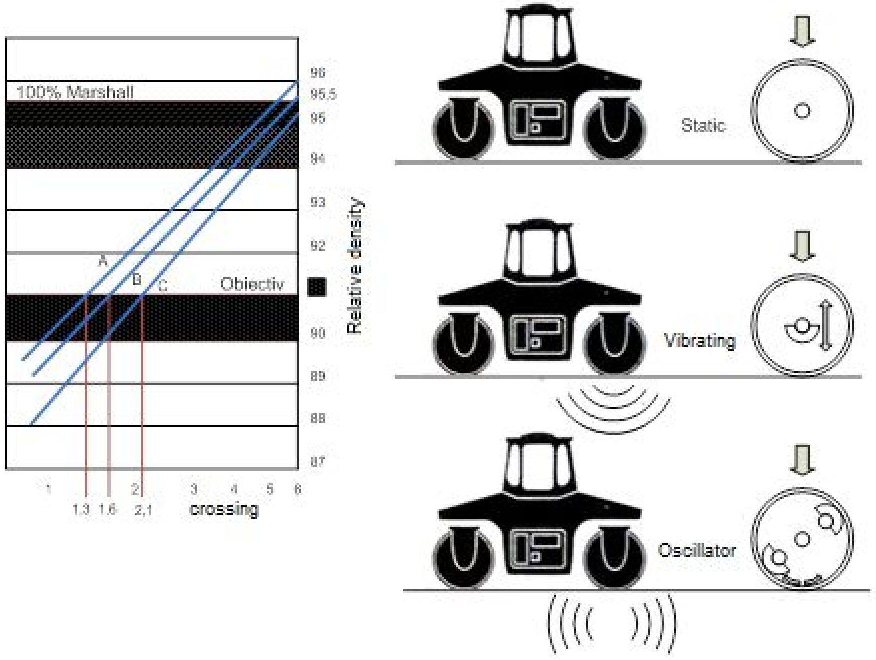


Figure 2.5. Influence of oscillations on compaction effect [27]

2.4 Dynamic characteristics of the vibratory rollers

Main technological parameters which influences the dynamic and vibration characteristics of the vibrating compaction equipment will continue to be briefly presented.

a) *The vibration frequency* is the primary factor that is determined both by the compaction technology, as well as the functional and constructive implications of the equipment. The researches performed [30, 31, 32, 33, 46] in the conditions of compaction of different materials shows that each system, consisting of fine particles of clay minerals, iron and aluminum hydroxides, colloidal silica, corresponds to its own frequency where the highest compaction effect is obtained.

Table 2.1. Recommended values for vibration frequency on compacting machines [27]

No.	The nature of the land	Frequency of vibrations, in *Hz*
1	Earth's non-cohesive	25 ~ 35
2	Earth's cohesive	20 ~ 30
3	Asphalt mixtures	35 ~ 50
4	Fresh concrete	45 ~ 70

The technology vibration regime is characterized by stable dynamic steps, with the vibration roller functioning in the post-resonance shown in the Figure. 2.8. such that

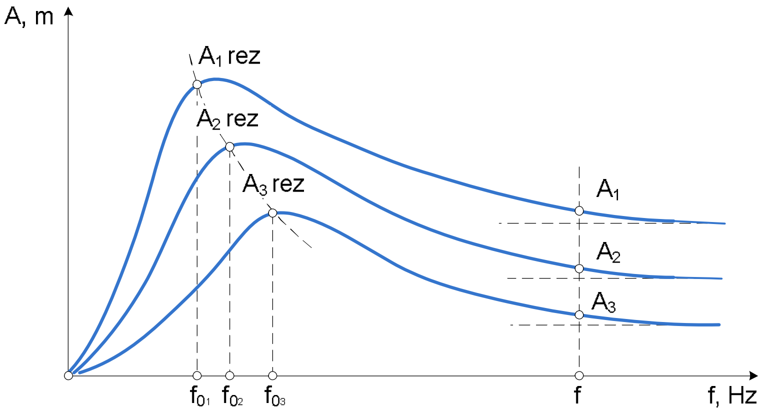


Figure 2.8. Technological vibration regime [44, 46]

b) A factor influencing the compaction depth is *the vibration amplitude*. Thus, for the different categories of soil, are recommended the values from the Table 2.2 [46]

Table 2.2. Recommended values for the amplitude of working vibrations in compactors

No.	The nature of the land	Amplitude of vibrations, in *mm*
1	Earth's non-cohesive	0,3 ~ 0,8
2	Earth's cohesive	1,5 ~ 5,0
3	Asphalt Mixtures (Hot)	0,25 ~ 0,40
4	Bitumen-stabilized strength layers	0,50 ~ 0,65
5	Cement stabilized strength layers	0,30 ~ 0,60

c) *Vibration Acceleration.* For harmonic vibrations, maximum throttle acceleration given by the relationship $A\omega^2$, has a decisive influence on the change in porosity.

So, in the Figure 2.9. is illustrated the variation of porosity as a function of the acceleration ratio $\Gamma = A\,\omega^2/g$for three types of soils of the same nature but with different granulometries. We note that from the value $\Gamma = 5 \ldots 7$upwards, the degree of porosity remains constant. Therefore, for rational design, is recommended the report. [44, 46]

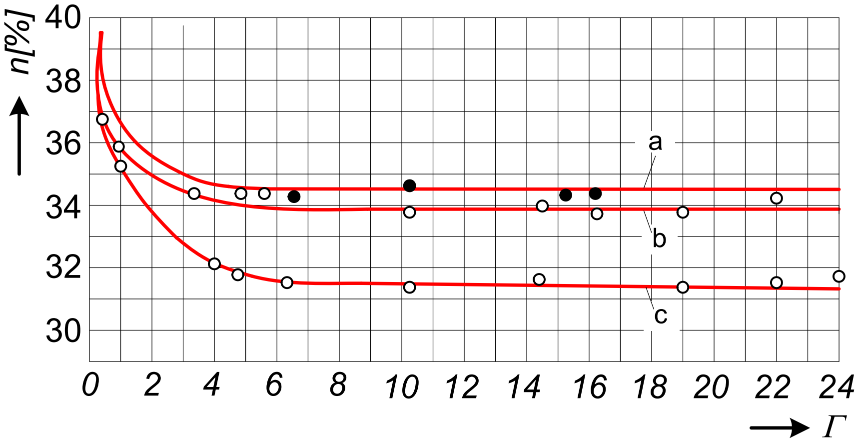


Figure 2.9. Variation of the porosity of the function of the acceleration ratio correlated with the granularity of the earth a, b, c. [34]

d) *Disturbing force* is the fundamental dynamic factor, for the vibrating compaction machine, because on the one hand it characterizes the magnitude of the amplitude, and on the other hand, dynamic field pressure and compaction (vibrations) to the contact area between the vibrating roller and the compacted medium.

e) *Displacement speed and number of passes represent the technological parameters with the highest weight in the productivity determination.*

$$v = 0{,}2\sqrt{f}[km/h], \tag{2.1}$$

where f is the frequency of vibrations, in *Hz*.

To achieve a proper compaction process it is advisable to take into account several correlations between the following technological, constructive and functional parameters of compaction equipment:

a) Uniform compression effort in the compaction process

In the case of compaction by static action, the maximum unitary effort is determined with the relation:

$$\sigma_{\max} = \sqrt{\frac{qE_{st}}{R}} \leq 0.9\sigma_r, \tag{2.2}$$

where *q*- is the specific linear loading of the roll;

E_{st} – earth deformation module;

R – the radius of the roller σ_r- breaking strength of the compacted layer.

In the Figure 2.10. are presented compression stress distributions under the tires of a compactor during the work process.

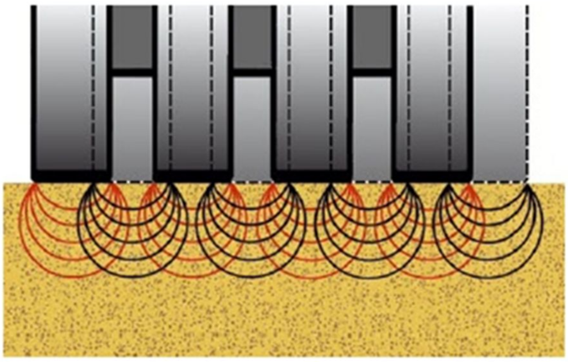


Figure 2.10. Depth distribution of compression effort under compactor tires

b) *Compaction depth*
c) *Number of passes*
d) *Specific linear loading*

Concluding the compaction process may be affected by the following variables factors:

- for non-woody soils:
  a) the soil category and coefficient of non-uniformity;

b) the water content;
c) the size of compaction effect;
d) the thickness of the layer that must be compacted;
e) the technical and functional characteristics of the compaction equipment.

- for cohesive soils:
  a) the soil texture including clay content and plasticity;
  b) the water content and degree of saturation;
  c) the amount of compaction effect;
  d) the thickness of the layer that must be compacted;
  e) the technical and functional characteristics of the compaction equipment..

This category of machines for earthworks, in particular, it is necessary to satisfy a specific criterion, fundamental, which embraces two contradictory aspects, namely:

- realizing vibration parameters on the vibratory roller for compaction;
- framing vibration parameters within acceptable limits at the mechanic's workstation in order to ensure ergonomic parameters and, at the same time, maintaining parameters that are characteristic of operational safety.

Unlike these desideratum, the structure of vibrating compaction machines has experienced an explosive development materialized by producing machines with high operational performance. Here are some constructive elements that should be highlighted:

- the chassis is articulated in the middle with the balanced parts on the two axles (front / rear);
- traction is achieved either only on the rear axle only or on both axles;
- the action of the inertial vibratory exciter and the displacement system is realized fully hydrostatic;
- the vibro-exciter is of inertial type with unidirectional or rotating disturbing force;

2.5. Technological capabilities

The technological capability of new compaction equipment expresses the level of technical performance expressed by the constructive and functional parameters that have a determining role in the quality and efficiency of the compacting process. [46]

Therefore, the technological capability can be determined by the performance levels of the constructive parameters, the functional parameters and the working capacity parameters.

a) *Constructive parameters*

From this category of constructive parameters that directly influence the compaction technologies are the following:

- *Geometric parameters:*
  - roller / tire diameter;
  - the width of the roller / tire;
  - the distance between the axles (wheelbase);;
  - turning rays;
  - ground clearance;
  - gauge dimensions (height, length, width);
  - the surface of the plate;
- *Gravimetric parameters:*
  - Total weight;
  - the weight distributed to the support surface on the compaction and / or rolling (supporting / displacement) devices. [46]

b) *Functional parameters*

From this category of functional parameters of compacting equipment with direct influence on the quality of the asphalt mixture compaction are:

- the speed of displacement during compaction;
- the static linear loading at roller compaction compaction surface;
- the technology vibration regime
- the technological push factor (Nijboer factor);

c) *Work capacity parameters*

CHAPTER III

Dynamic analysis of interaction vibratory drum-terrain for earth

3.1. Generalities

Mechanical systems have, in their structure, motion elements, rigid, elastic bodies and joints. As regards these elements of motion, they are materialized by bodies having different geometrical configurations, and which are linked to one another by the joints. Thus, the role of the joints is to enable the movement of the elements or to impose restrictions or constraints on the relative movements of the components of the mechanical system. [46]

3.2. Comparative analysis methods of the compaction process through vibration

For the compaction of the earth are used the dynamic rolling-compression processes. The contact between a cylindrical roller and the earth surface transmits a stationary field of harmonic vibrations that have the task of producing the wave effect over the entire depth of the layer. [45].

Therefore, were analyzed the following viscoelastic models: Maxwell, Voigt-Kelvin, Voigt-Kelvin-Hooke, Zener, Voigt-Kelvin-Newton and Voigt-Kelvin-Hooke-Newton viscoelastic, which in some conditions give very precise information about the real-time behavior of the land.

3.2.1. Voigt-Kelvin Model (E/V)

Cinematic excitation of type $x(t) = A_0 sin\omega t$ makes the system to transfer the energy to the base, namely to lead to a dynamic response in ties which is represented by the viscous force $Q(t) = c\acute{x} + kx$. [45]

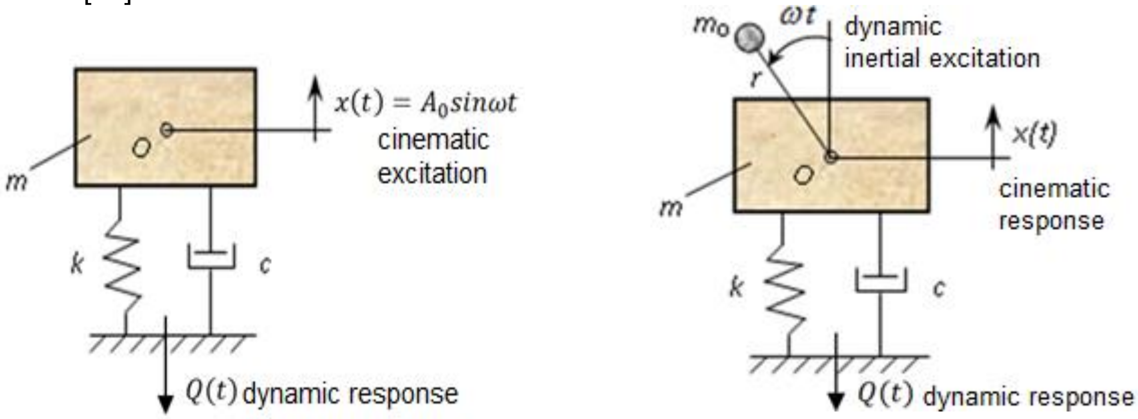


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Figure 3.1. Voigt-Kelvin Model [45]

3.2.1.1. Response of E/V system at dynamic harmonic inertial excitation

Thus, the following analysis steps can be determined [41, 45, 129]:

a) inertial excitement in rotational motion of the mass m_0 with radius r and angular speedω, is shown by the harmonic force function as follows:

$$F(t) = m_0 r\omega^2 sin(\omega t) \tag{3.2}$$

b) the instantaneous response is of the of the form:$x(t) = Asin(\omega t - \varphi)$, but the reaction force is$Q(t) = Q_0 sin(\omega t - \varphi - \theta)$.

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

$$m\acute{x} + c\acute{x} + kx = m_0 r\omega^2 sin(\omega t)$$

3.2.2. Maxwell Model (E-V)

Linear physical behavior of the terrain is described by the given model. It is schematized by serially linking a resilient element with a viscous element. In the figure 3.2.a is illustrated the symbolic representation of the kinematic excitation model, and in the figure 3.2.b is illustrated the dynamic excitation model, which is analyzed [40, 45, 129].

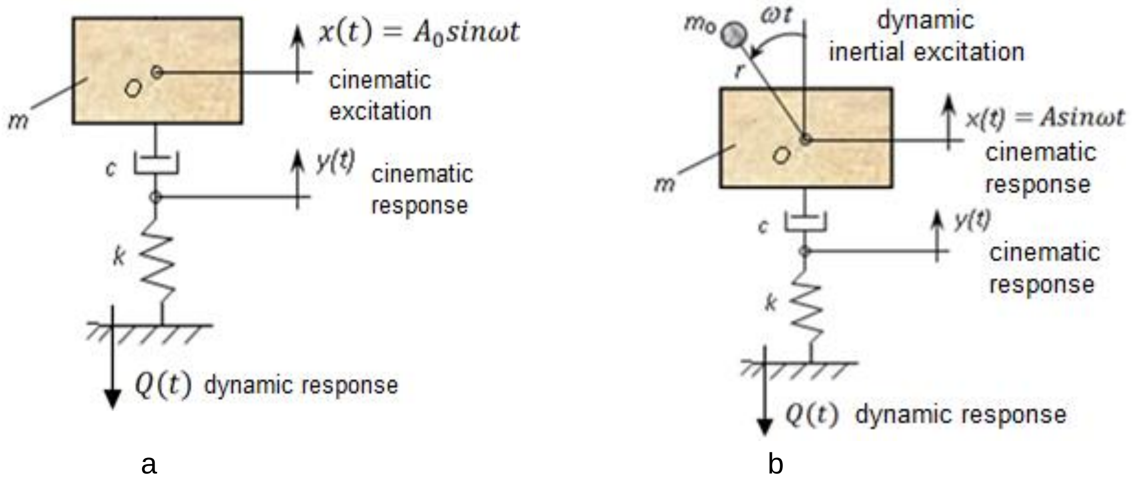


Figure 3.2. Maxwell Model [45]

3.2.2.1. Response of E-V system at dynamic harmonic inertial excitation

3.2.3. Zener Model E/(E-V) and system response E/(E-V) to harmonic inertial dynamic excitation

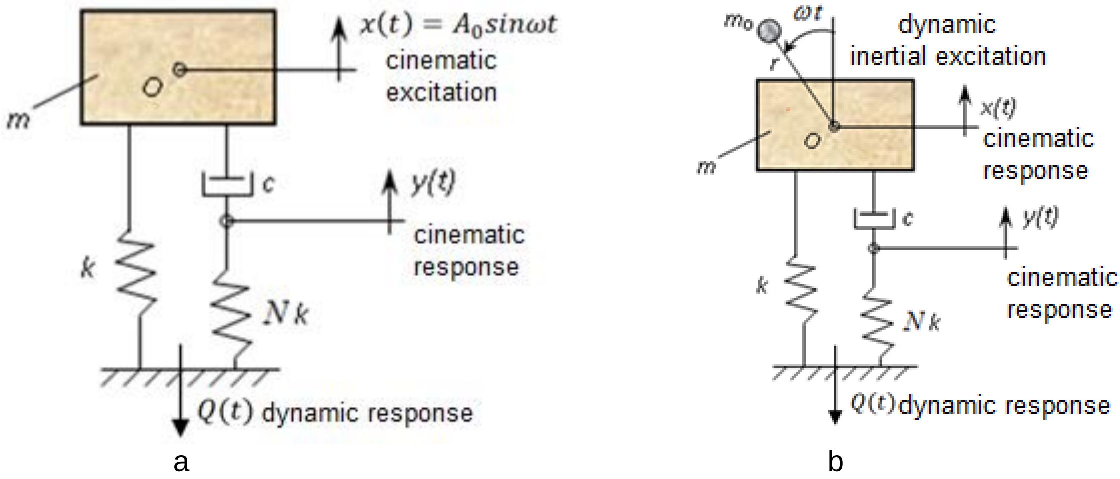
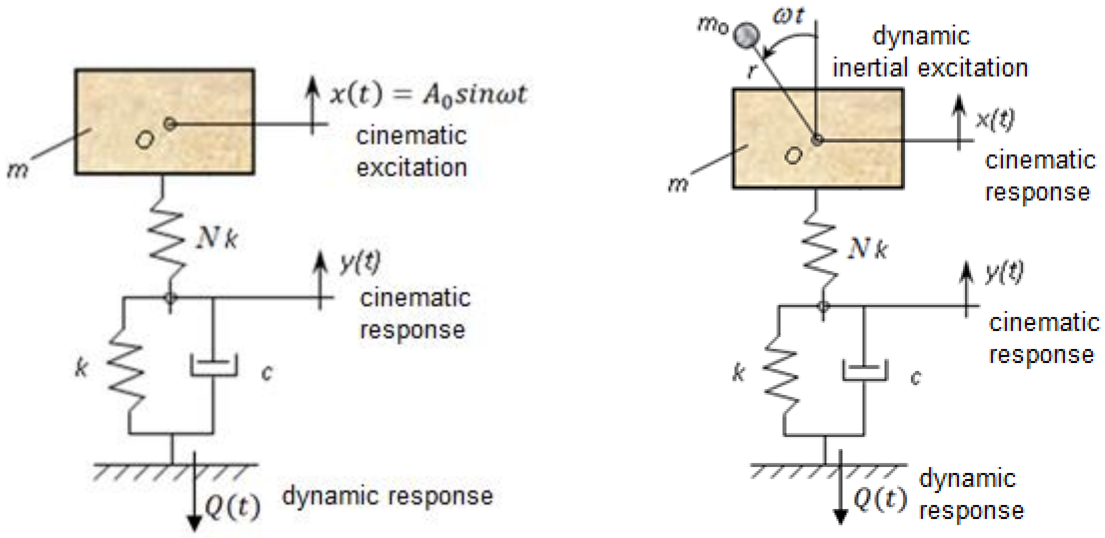


Figure 3.3. Zener Model [45]

3.2.4. Voigt-Kelvin-Hooke Model E - (E/V) and system response E- (E/V) to dynamic harmonic inertial excitation

This model is schematized by a system with a predominantly elastic deformation. It is made by serially binding of an elastic multiple element with an assembly made up of an elastic element coupled with a viscous one. In the Figure 3.4.a is illustrated the symbolic representation of the model with kinematic excitation, and in the Figure 3.4.b the model with dynamic excitation, which is studied. [40, 45, 129].



a b

Figure 3.4. Voigt-Kelvin-Hooke Model [45]

3.2.5. Voigt-Kelvin-Newton Model V - (E/V) and system response V-(E/V) to dynamic harmonic inertial excitation

The linear schema illustrated in the Figure 3.5.b shows that at dynamic excitation with rotating disturbing force $F_0 = m_0 r\omega^2$ the system's response consist of x(t) and y(t) as instantaneous kinematics (displacements) and instantaneous dynamic size Q(t) as a reaction force at base, namely at vibratory-field contact. [45]

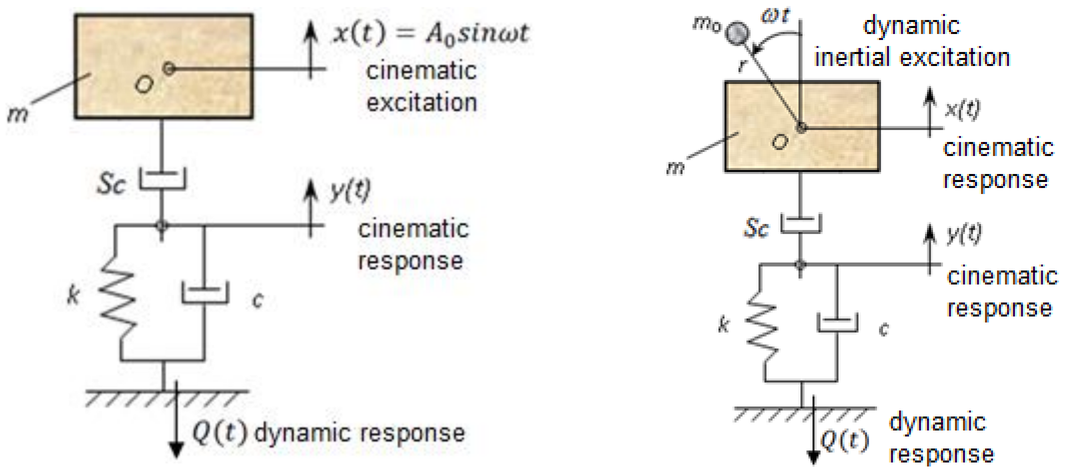


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Figure 3.5. Voigt-Kelvin-Newton Model [45]

3.2.6. Voigt-Kelvin-Hooke-Newton Model (E-V) - (E/V) and system response (E-V) - (E/V) to dynamic harmonic inertial excitation

The given model is a linear model with viscous deformation. It is made up by the series binding of three elements: a viscous element, an elastic element, and an elastic element assembly tied in parallel with a viscous element. In the Figure 3.6.a, is illustrated the symbolic representation of the kinematic excitation model, but the Figure 3.6.b is illustrated the synamic excitation model, which is analyzed [40, 45, 129].

3.3 Vibratory movement of the drum-terrain assembly

The dynamic study of vibration compacting machines is formulated under the assumption of the hypothesis of linear elastic behavior and damping with harmonic inertial excitation.

Thus, the results are accurate enough to receive useful answers in most cases, the errors being quite small [40, 45]. This theory is necessary for preliminary determinations of some constructive and functional parameters of the working body.

In this way we will adopt the following hypotheses for calculating the dynamic behavior of the vibratory-field assembly [42, 45]:

- the earth, as a rheological environment in general, is represented by the composite Voigt E / V model, and outside the resonance area of the simple Hooke E model;
- the dynamic model of the vibratory-field system does not take into account the mass of the earth (the inertial properties of the earth are neglected);
- the two-mass system performs only vertical movements in one plane and in the vertical direction;
- the working tool that performs the compaction (plate, roller) remains always horizontally (rotating vibrations are neglected);
- the unidirectional vibration generator is positioned in such a way that the disturbing force that is acting vertically passes through the center of gravity of the compactor (plate, roller) that is on its symmetry axis [37,45];
- the axes of rotation of the eccentrics have small displacements so they are not taken into account (inertial forces that appear due to low displacements).

3.3.1. Vibration of vertical translation, the dynamic response for viscoelastic model

Amplitude of vibrational movement [41, 45], in the case of the dynamic model of the earth, schematized after Voigt-Kelvin E/V conformable Figure 3.7 will be determined on a stable basis dynamic inertial excitation with $P_0 = m_0 r \omega^2$ and harmonic with $P = P_0 cos\omega t$.

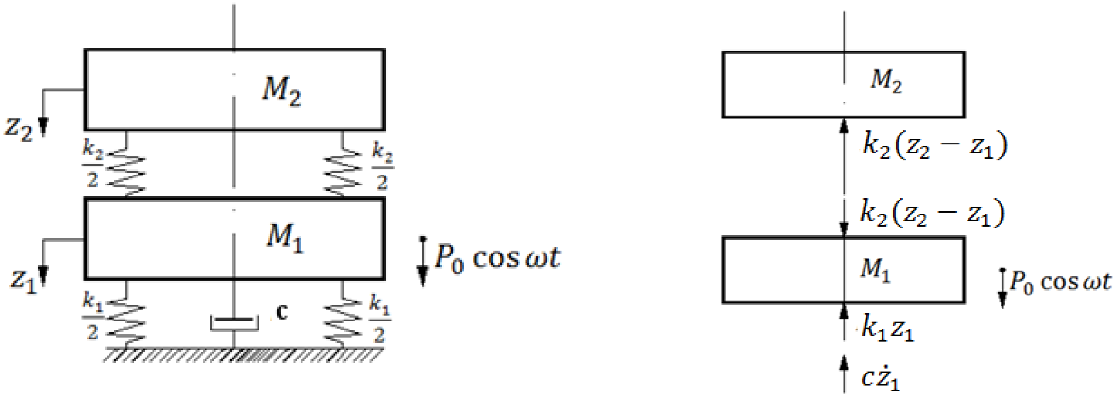

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Figure 3.7. The mechanical model of the ensemble drum-terrain with two masses of vibration, a) The dynamic model; b) Scheme of forces under dynamic equilibrium instantly [41,45]

3.3.2. Dynamic response for the elastic model

Amplitude of vibrational movement, in the case of the dynamic model of the earth, Hooke (E) schematically in figure 3.8. is similar to the previous approach [41, 45].

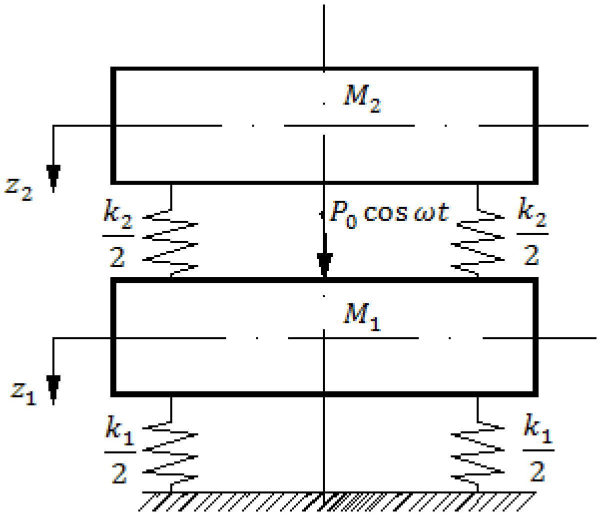


Figure 3.8. The idealized mechanical model of the ensemble drum-terrain with two masses in vibration [41, 45]

3.3.3. Dynamic response for viscoelastoplastic model

Amplitude of vibrational movement, in the case of the dynamic model of the earth, as viscoelastoplastic type V/(E-P) is characterized by a stable working regime [41, 45] (Figure 3.10.).

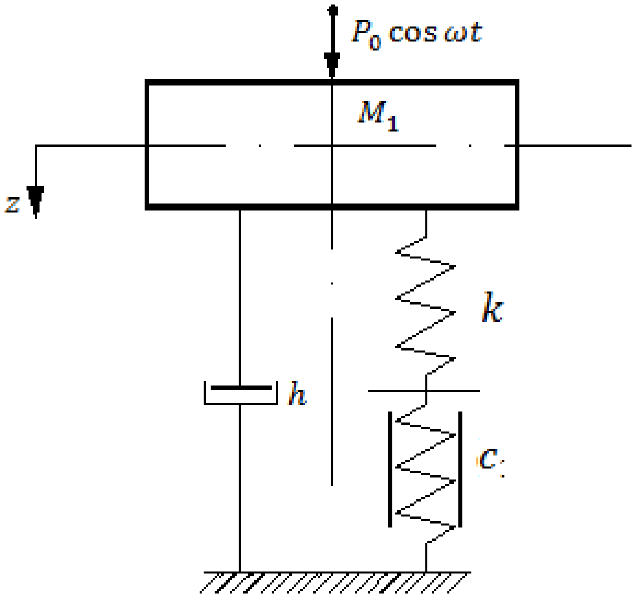


Figure 3.10. The dynamic model of the assembly drum-terrain with one mass of vibration, and the molded earth V/(E-P) [41, 45]

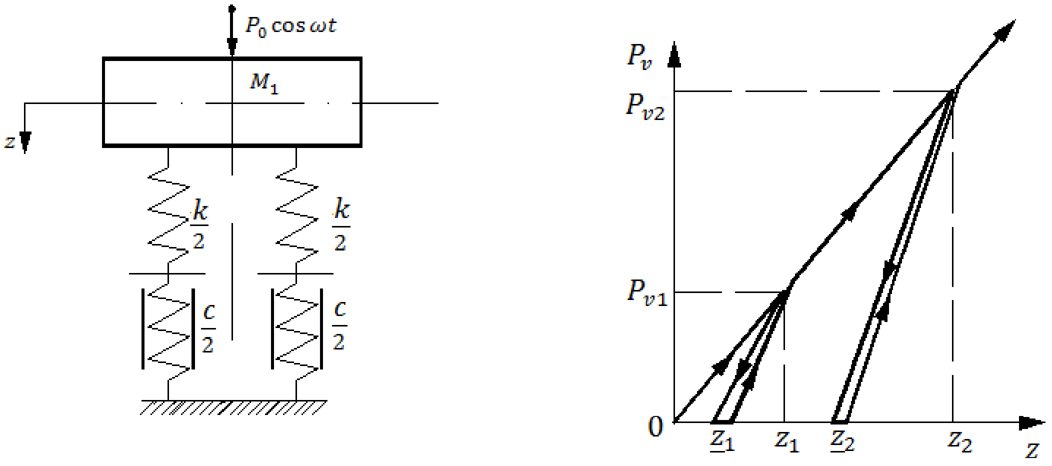
3.3.4. Dynamic response for elestoplastic model E-P

Amplitudes of vibrational movement, in the case of the compound model E-P [41, 45], will be specified for the assembly model drum-terrain with two masses in vibration and operating outside the resonance zone, thus the influence of depreciation is negligible, namely h = 0, the value of the mass amplitude M_1 will be obtained if in the expression (3.42) will change on k_e with its value in (3.48), so we have:

$$A_1 = \frac{P_0\left(\frac{k_2}{M_2}-\omega^2\right)}{\left(\frac{k.c}{k+c}+k_2-M_1\omega^2\right).\left(\frac{k_2}{M_2}-\omega^2\right)-\frac{k_2^2}{M_2}} \tag{3.51}$$

3.3.5. Dynamic response for the system with a weight

a) The rheological model E-P



a B

Figure 3.11. The dynamic model of the assembly vibrogenerator-ground with a single mass in vibration where the earth is modeled E-P. a) symbolic representation; b) characteristic curve of linear deformation of the earth [41, 45]

b) The rheological model V/E-P

3.4. Variable vertical translation vibration and rotation around the horizontal transverse axis

3.4.1. Dynamic model of the vibrator compactor-terrain system

3.4.2. Pulses of the vibratory field compactor assembly

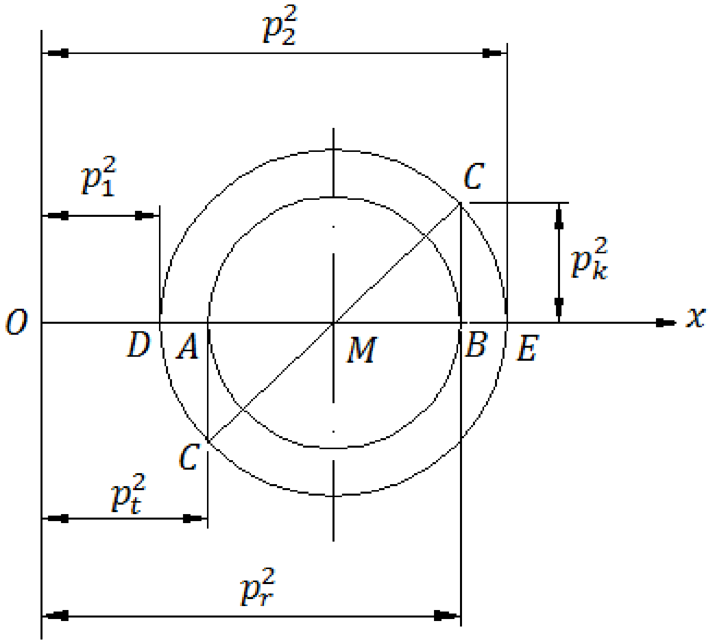


Figure 3.14. Graphic representation of similar pulses „ Mohr circle" [39, 45]

CHAPTER IV

Analysis of contact parameters of drum compactor terrain

Effect of drum-earth contact is based on the efficient operation of the permanent machine. This requires the compaction process to be completed before the threshold value for the rigidity of the earth is reached, and namely, not to operate the ground-breaking machine.

4.1. Static linear deformation modulus of the soil

Experimental determinations for establishing the static linear deformation modulus E_{st} of linear earth deformation and its dry density ρ_d were noticed the existence of a correlation between the values of these two characteristic parameters. The main types of foundation ground, with appropriate humidity, W frequently are encountered: [46]

- sand, non-cohesive earth: W = (5...12)%;
- poor cohesive earths: W = (12...15)%;
- ballast.

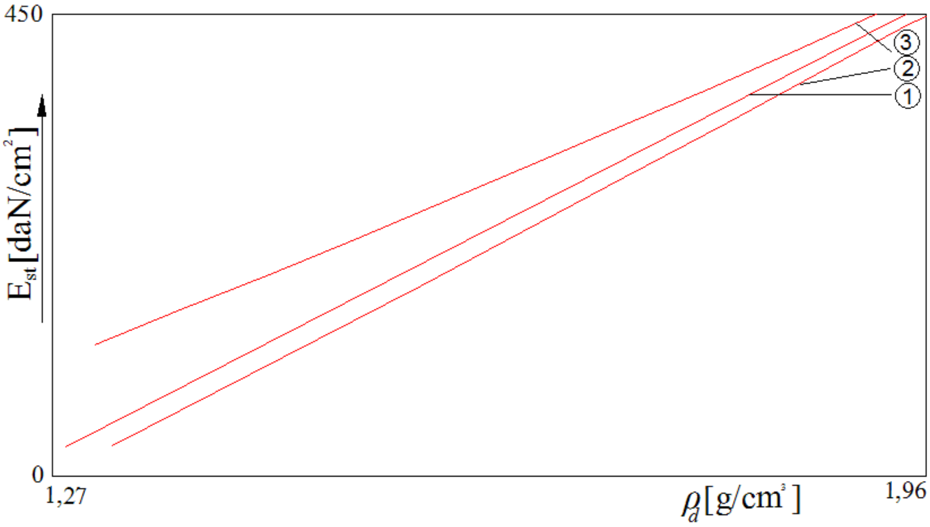


Figure 4.1. Dependence of static modulus of linear deformation on density in a dry state, namely 1. for sand, non-cohesive earth;
2. for poorly cohesive earths; 3. ballast.

4.2. Width of the footprint contact between drum-terrain according to the dry density of the soil

The experimental determinations have established that the width b^* of the roll footprint at the contact with the ground is within he range of values:

$$b^* = (0,1 \dots 0,2)D_r \tag{4.6}$$

4.3. Soil layer thickness dependence in respect with dry density

On the basis of linear interpolation, relations of interdependence between the parameters specific to the compaction process can be established, namely:

$$h_C = 0,667(1 - D_c)b^* \text{ [cm]}, \tag{4.10}$$

$$h_C = 4,44(1 - D_c)^2 D_r \text{ [cm]}, \tag{4.11}$$

$$h_C = 4,44(1 - \rho_d/\rho_{dmax})^2 D_r \text{ [cm]}. \tag{4.12}$$

4.4. Compaction layer of soil

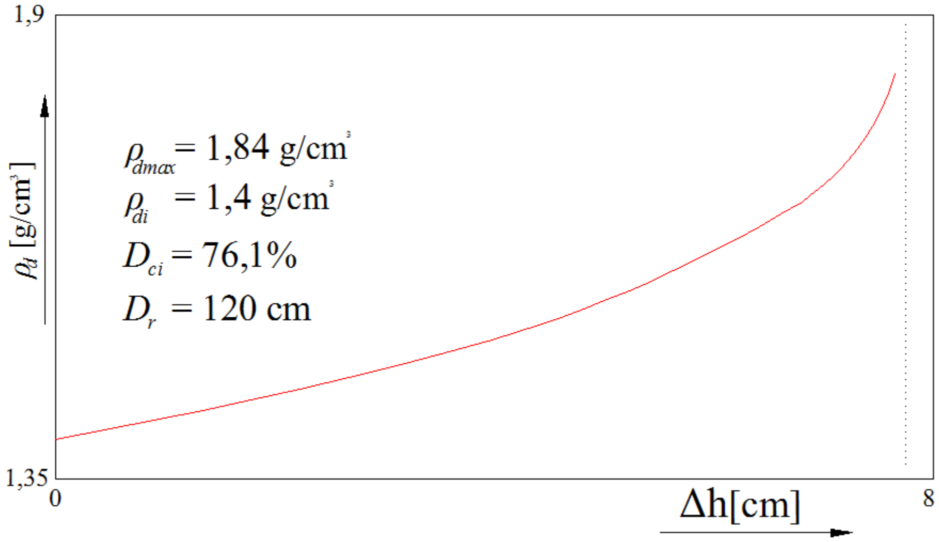


Figure 4.2. The dependence of the density in the dry state according to the compaction of the earth

By compression, a maximum density is obtained either by increasing (from loose lands) or by decreasing (from compact blocks), which indicates that the compacted state is a limit value for a particular structure.

4.5. Static linear deformation modulus dependence according to the compaction layer

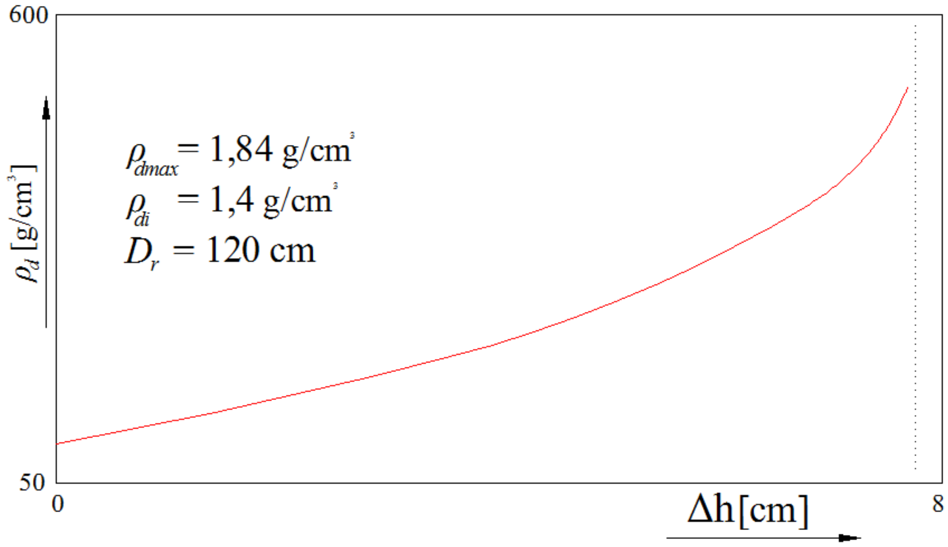


Figure 4.4. The dependence of the static deformation module on the compression function, for a poor cohesive earth pattern [46]

4.6. Rigidity coefficient in respect with the compaction layer

In the diagram in the Figure 4.5 is presented the dependence of the coefficient of rigidity of the land according to the compaction Δh, Based on relation (4.29) developed for poor cohesive earth, in the case of particular earth of the poorly cohesive earth, as previously defined.

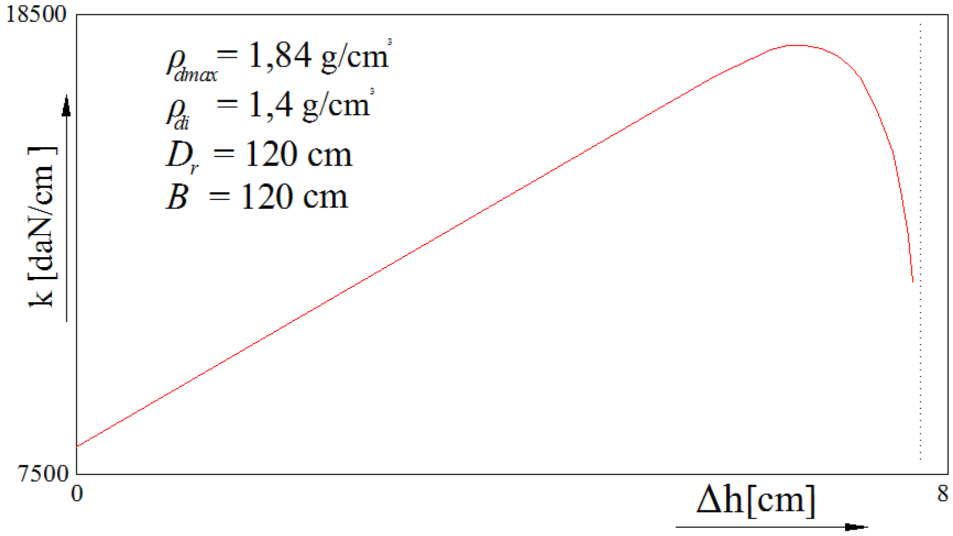


Figure 4.5. Dependency of the stiffness coefficient by compression (for a poor cohesive earth) [46]

4.7. Resistance soil in respect with the compaction layer Δh

In the diagram in The Figure 4.6. is illustrated the variation of the elastic force of resistance to the compaction of ground, depending on compressionΔh, based on relation (4.30) developed for poorly cohesive earths.

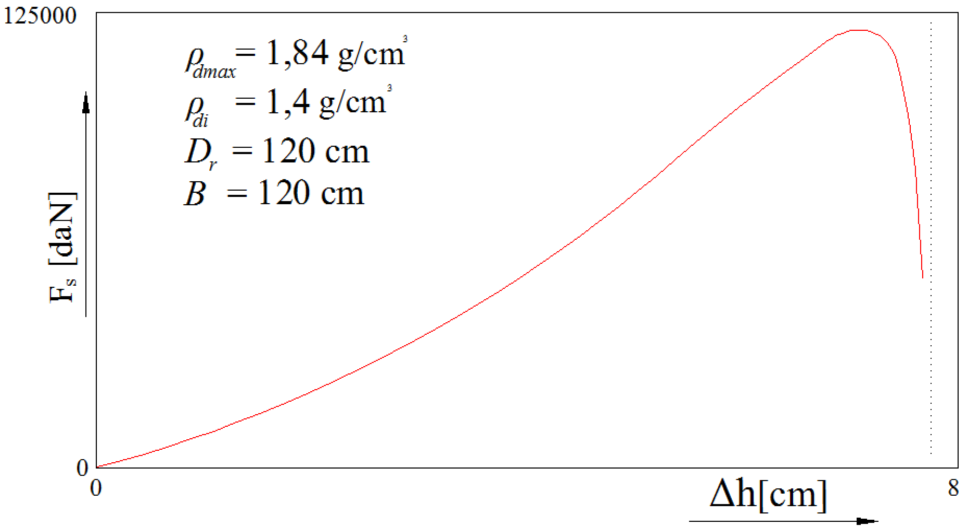


Figure 4.6. Dependence of elastic force of resistance to compaction depending on compaction. (poor cohesive earth model)

The diagram reveals, as well, the nonlinear behavior of the earth in the overall compaction process. [46]

Curve $F_S - \Delta h$ from the Figure 4.6 might be interpreted as representing the holding capacity of the land corresponding to the compaction at a certain point in the compaction process. [46]

4.8. Axial strain (tensions) soil in respect with the compaction layer

The unitary axial effort (voltages)σ_C evolved in the field by the dynamic action of the compacting machine, summed up both the direct effect of the action of the machine on the ground, as well as the reaction of the compacted field on the machine. Thus, it can be stated with certainty that this parameter reflects the interaction between the compactor and the ground in the technological process and that its monitoring is an important indication in knowing the stage of the compaction process. [46]

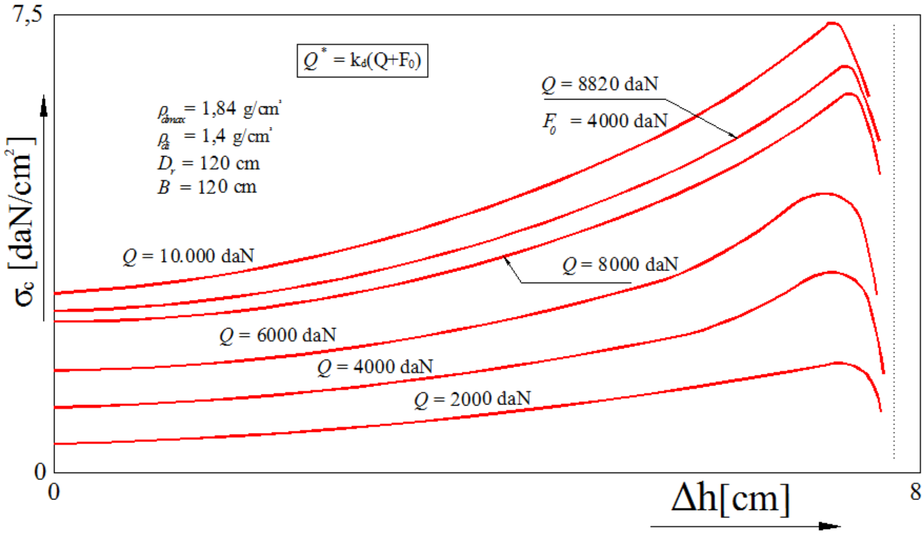


Figure 4.7. The dependence of the unitary axial compaction effort on the compaction, for a poor cohesive earth model [46]

4.9. Essential parameters involved in drum-terrain interaction

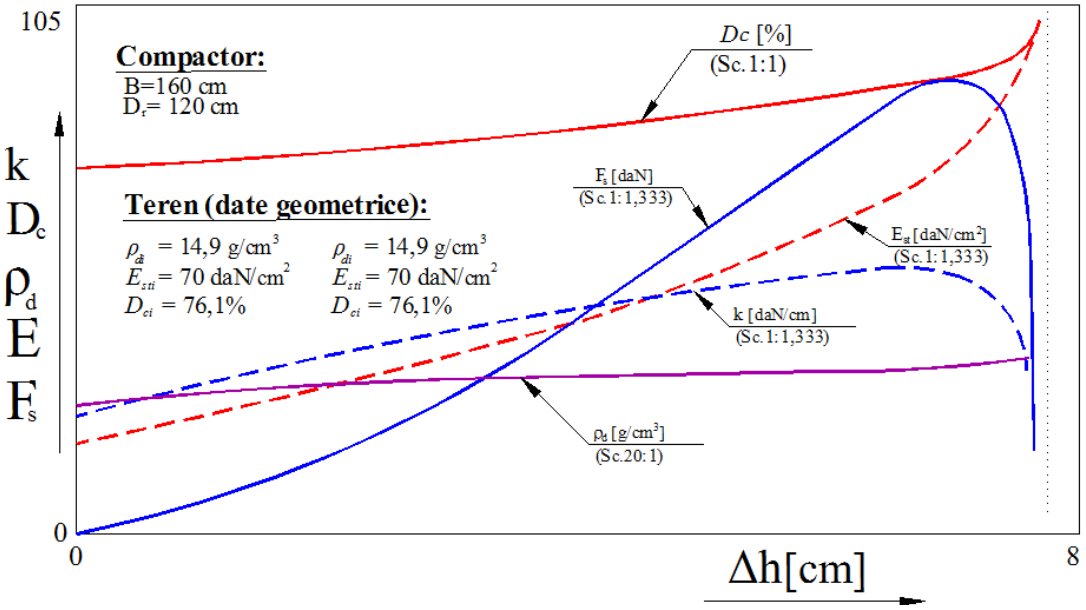


Figure 4.8. Global dependence on essential parameters involved
in the compactor- ground interaction process,
for a poor cohesive earth model [46]

Thus, can be observed the evolution of the technological performance and efficiency of the compaction process of the terrain reflected by the evolution of the compaction degree, the dry density and the static linear deformation module of the earth. [46]

The coefficient of rigidity of the land is, within the model of land behavior, the element through which is materializes the ground response reaction on the compacting machine, and its using in the equation of motion of the machine allows the determination of its optimum working regime in order to grant it correlative with the technological compaction load that must be achieved by the compaction technological equipment.

CHAPTER V

Experimental testing for the validation of dynamic compaction technology.

5.1. Generalities

For the use of land for the construction of road structures, are required both additive materials and adequate technologies which ensure the stability and stability parameters at the level of the normative requirements.

In this context, this paper highlights the effect of enzymes in blending with natural soil, mineral aggregates and additives. For certain categories of land with significant content of clay mixed with sand and mineral aggregates with appropriate treatment of enzyme stabilizers were obtained remarkable experimental results. Thus, the characteristics of enzyme-stabilized structures can be defined on the basis of the mechanical strength σ of the longitudinal elastic modulus E_z in the vertical direction, the elastic modulus of elasticity E_v and the coefficient of stiffness k in the vertical direction.

The presence of enzymes in the mixture of material is noted, under appropriate dosing, mixing and homogenization conditions, by modifying Poisson's coefficient, noted as υ. In this case, by increasing values of υ to the maximum limit $\upsilon_{\max} = 0,5$ it is noticed the increasing of the volume elastic modulus, increasing the resistance and increasing the rigidity of the structure.

5.2. Parametric experimental researches concerning grounds stabilized with enzymes.

5.2.1. The rigidity of the processed stabilized ground structure.

In the process of mixing the mixture ground-mineral aggregates must be assured the optimal dose of supply, in atomized condition with enzymes or polyenzymes that would occupy the porous spaces by reducing the water content from the natural porous network.

Current technologies with automatic control and computer monitoring are capable of providing a wide variety of technical solutions [13]

For these reasons, the processed material in the form of earth stabilized with enzyme, must have the porous network with high content of enzymes for increasing the coefficient Poisson and the increase of resistance at the process of freezing (freezing-thaw).

In the field of elastic deformation for the road structure put into practice, vertically, as a consequence of compaction through vibration, the rigidity can be estimated as follows:

$$k = C_z S \qquad (5.1)$$

Where k is the rigidity coefficient, in the elastic field;

C_z - coefficient of uniform elastic contraction corresponding to the area S of the contact rectangular surface; [47, 51]

For the coefficient of uniform elastic contraction, it is applied the relation

$$C_z = \alpha \frac{E_Z}{\sqrt{S}} \frac{1}{1-\upsilon^2} \qquad (5.2)$$

Where α is the form coefficient of the real surface which is materialized through a contact board, with values within in the range 0,8 ÷ 1,5.

In the case of “in situ” attempts for a certain ground category, one can use “test plate” with a rectangular surface of area S’ which allows the calculation of the rigidity coefficient k’ for the “test field” with the relation:

$$k' = \alpha \frac{E_Z\sqrt{S'}}{1-\upsilon^2} \qquad (5.3)$$

The rigidity coefficient k for the real surface S of rectangular shape (the contact spot) between the vibrating roller and the stabilized ground layer can be calculated using the formula:

$$k = \frac{\alpha E_Z\sqrt{S}}{1-\upsilon^2} \qquad (5.4)$$

From the relations (5.3) and (5.4) can be estimated the value of k in relation to the value of k' determined experimentally, as follows

$$k = k'\sqrt{\frac{S}{S'}} \qquad (5.5)$$

For the test plate with S = 4500 cm2 the rigidity coefficient k' for various field categories was experimentally determined under dynamic regime of vibrations of resonance (Table 5.1.) [56].

Table 5.1. Experimental values of rigidity k' with the dynamic teste plate

No.	Nature of Stabilized Ground Layer	Rigidity Coefficient k', MN/m
1	Loose sandy soil Gravel (3 ÷ 7) mm with sand	44,0
2	Loose loamy fine sand Gravel (7 ÷ 15) mm with loamy sand	67,5
3	Medium grained and light loamy loose sand	90,0
4	Medium grained sand until the sea	95,6
5	Gravel (7 ÷ 15) mm with pre compacted ground Clay with compacted ground	120,0

5.2.2. Modulus of longitudinal elasticity.

For a cylindrical sample extracted from the stabilized/compacted layer, subjected to the uniaxial compression, according to requirements national norm SR 8942/6-75 the axial elastic modulus E_z is determined as follows:

$$E_Z = \frac{4}{\pi}\frac{F_Z}{d^2-d_0^2}\frac{h_0}{\Delta h} \qquad (5.6)$$

Where F_z is the axial force applied centrically;

d_o - initial diameter of uncompressed sample;

h_o - initial height of uncompressed sample;

d - final diameter of the median transversal section after compression;

h - final height remained, of the sample, after compression;

Δh - variation of height (compaction) of the sample under compression force, so that

$\Delta h = h - h_0 < 0$

Therefore, based on 1500 of samples collected from the ground layer stabilized with enzymes and compacted with a vibrating roller, there were determined the values of the modulus E_z.

Depending on the amount of enzyme mass, reported to 100 kg of milling, mixed, compacted ground, that is at the percentage dose ε, %, were obtained the values of longitudinal elastic modulus E_z presented within the Table 5.2.

Table 5.2. Modulus E_z depending on the ε

ε,%	0,1	0,2	0,3	0,4	0,5	0,6
E_z, MN/m^2	5,81	6,50	7,80	8,78	9,15	10,21

5.2.3. Coefficient of Poisson.

In the case of uniaxial compression under direction Z with the force F_z the process of axial deformation characterized through specific deformation $\varepsilon_z = \frac{h-h_0}{h_0} = \frac{\Delta h}{h_0}$ is logically accompanied by the transversal deformation from the median plan, expressed by $\varepsilon_y = \frac{d-d_0}{d_0} = \frac{\Delta d}{d_0}$, so that $\varepsilon_y = \upsilon\, \varepsilon_z$ [13, 33, 57].

As a result, the coefficient of Poisson υ may be determined with the relation

$$\upsilon = \frac{h_0}{d_0}\frac{\Delta d}{|\Delta h|} \tag{5.7}$$

The experimental results have shown υ values of between 0.42 and 0.485 for the 1500 samples collected "in situ".

Table 3 shows the values of the coefficient of Poisson depending on the percentage does ε of the enzyme stabilizer [47, 51]

Table 5.3. Values of the coefficient of Poisson depending on the ε, %

ε,%	0,1	0,2	0,3	0,4	0,5	0,6
υ	0,421	0,442	0,453	0,465	0,475	0,485

5.2.4. Modulus of volumetric elasticity.

For fields with large surfaces and wide spaces subjected to vibrations or undulating processed wave unidirectional propagation, the volumetric modulus E_v can be determined as follows:

$$E_v = E_Z \frac{1-\upsilon}{(1+\upsilon)(1-2\upsilon)} \tag{5.8}$$

It is found that by changing the porosity and supply of voids with stable fluid like substances, the coefficient of Poisson increases until the limit value ($\upsilon_{\max} = 0{,}5$, so that $\upsilon < \upsilon_{\max}$).

Table 5.4. Modulus E_v depending on modulus E_Z and υ

υ	0,421	0,442	0,453	0,465	0,475	0,485
E_Z, MN/m^2	5,81	6,50	7,80	8,78	9,46	10,21
E_v, MN/m^2	14,96	21,83	31,25	45,86	67,26	117,80

The samples taken on layers of ground stabilized with enzymes within the dose ε = 0,5% were used in order to be followed in time. The volumetric elastic modulus dynamic (deformation) measured "in situ" at 35m from the compaction source through vibration, at certain time intervals, is given in the Table 5.5**.**

Table 5.5. Volumetric elasticity modulus E_v in time [54, 55]

Time, hours	0	16	24	48	72
E_v, MN/m^2	67,5	70,5	96,3	101,8	109

The rheological evolution with regard to time points out a stable asymptotic increase, as results from the experimental data contained within Table 5.2. Therefore, the rheological law established by the authors of the present paper is under form [50]

$$E_v(t) = \frac{0{,}877 + 15t}{0{,}13t + 0{,}013}$$

With $E_v(0) = 67,46$ MN/m^2 at the moment t = 0.
The temporal variable t is expressed in hours.

For the results obtained experimentally, within Figure 5.1, it appears the curve of variation of the modulus $E_v(t)$ in relation to time.

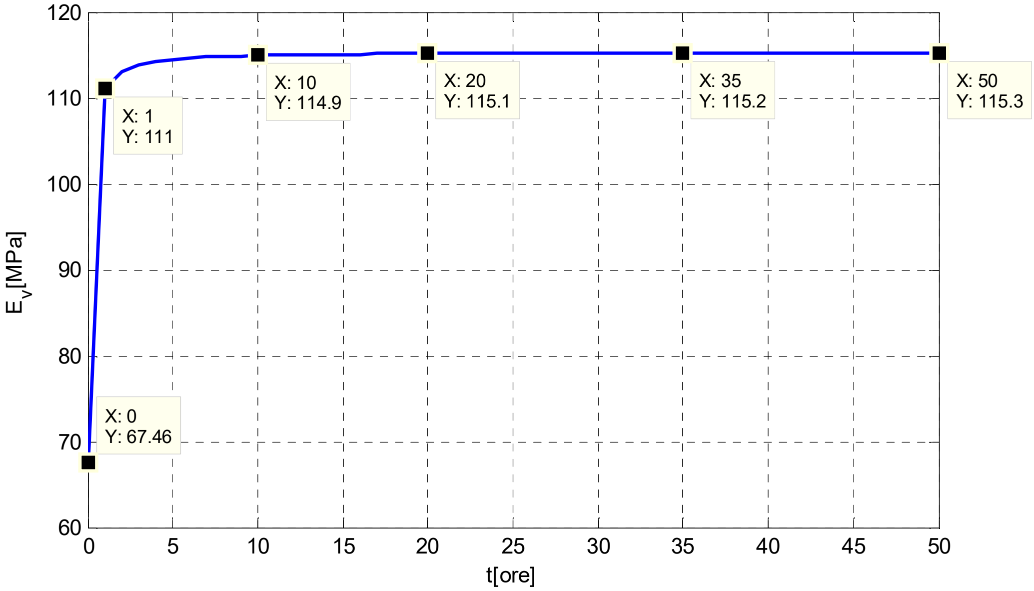


Figure 5.1. Variation of volumetric elasticity modulus in relation to time

5.2.5. Californian index CBR

The Californian index of bearing capacity is expressed under the form of CBR=$\frac{F_p}{F_s}$ for the depth of penetration Δp, where F_p is the effective penetration force, and F_s is the standard force corresponding to the values Δp = 2,5 mm and Δp = 5 mm. For grounds stabilized with enzymes were obtained the values from Table 5.6. [52, 53]

Table 5.6. Index CBR, % for stabilized ground

Sample Lot	Average Value of the Effective Penetration Force	$CBR_{2,5}$, Δp =2,5 mm F_s =13,2 KN	CBR_5, Δp =5 mm F_s =20,0 KN
I	8,3	63	-
	11,0	-	53
II	7,5	56	-
	9,2	-	46
III	7,8	58	-
	9,3	-	46
IV	9,45	71,5	-
	13,11	-	66
V	Index CBR, % for untreated ground		
	3,11	23,55	-
	3,86	-	19,32

5.3. Determination of resistance to single-axial compression on stabilized soil samples.

Thermally untreated stabilized earth specimens, taken from the layers collected from the site, were kept under normal laboratory conditions at +200 °C until 7 days, being subsequently subjected to the monoaxial compression test. Thermally treated stabilized earth specimens were taken from samples compacted to optimal humidity, being kept for 48-72 hours under normal laboratory conditions at +200 °C before being exposed to freeze-thaw cycles.

The minimum duration of the frost and thaw cycles to which the analyzed samples were subjected was set at 24 hours, to which the analyzed samples were subjected was set at 24 hours, accordingly for the maximum duration of 96 hours at -100 ° C in the Liebhart laboratory refrigerator. After each freezing and thawing period, measurements on sample specific parameters (volume, mass, density) were performed to estimate how alternative frost - freeze cycles affect the behavior of stabilized earth, especially the resistance parameters. Recordings of the corresponding mass measurements and the density of samples subjected to 3 freeze / thaw cycles are shown in Table 5.7, with no changes in sample height being observed. [47, 48, 49, 130]

Table 5.7. Sample mass values subjected to 3 cycles of frost - thaw

Determination	Mass of the sample(g)					
	P1	P2	P3	P4	P5	P6
initial	1830,46	1618,35	1757,11	1661,96	1717,03	1778,22
frost	1811,57	1597,18	1740,26	1645,03	1689,15	1756,43
thaw	1797,39	1584,02	1726,87	1630,09	1684,58	1756,66
frost	1801,58	1587,84	1730,34	1636,89	1682,03	1752,15
thaw	1782,21	1568,96	1713,01	1628,2	1675,12	1740,07
frost	1786,36	1597,88	1746,68	1649,79	1686,93	1749,33
thaw	1761,23	1586,95	1735,12	1638,23	1672,85	1738,54

The method used consisted of continuously applying to the earth specimen an evenly increasing axial load to determine the single axial compressive strength and the specific axial deformation corresponding to the reach of the monoaxial compressive strength. The imposed deformation velocity was 0.02 mm / min. [130]

It is mentioned in SR 8942 / 6-75 that the determination of the compressive strength of the monoaxial compression is carried out on cylindrical specimens while maintaining a ratio equal to about 2 between the height (h) and the diameter (d). Taking into consideration the fact that the cylindrical specimens that were taken, did not have the required dimensions, were applied standard resistance correction factors. according to BS 1881, Part 120 (Table 5.8). [130]

Table 5.8. Resistance correction factors (BS 1881, Part 120)

Height / Diameter ratio (h/d)	Factors of resistance correction
2.00	1.00
1.75	0.97
1.50	0.92
1.25	0.87
1.00	0.80

Monoaxial compressive strength values obtained for thermally untreated soil samples (Table 5.9) and subjected to freeze-thaw cycles (Table 5.10) were corrected by the factors corresponding to the h / d ratio. [130]

Table 5.9. Specific resistances at monoaxial compression on thermally untreated stabilized land samples

Sample code	Specific resistance to uncorrected average monoaxial compression		Raport h/d	Correction Factor (BS 1881, Part 120)	Specific Resistance to Monoaxial Compression Compensated	
	(σ, N/mm^2)	(σ, kPa)			(σ, N/mm^2)	(σ, kPa)
Land stabilized untreated thermally						
P1	0,330	330	1,36	0,89	0,294	294
P2	0,277	277	1,41	0,90	0,247	247
P3	0,407	407	1,34	0,89	0,360	360
P4	0,412	412	1,20	0,86	0,346	346
PN	0,176	176	0,97	1,76	0,170	170

Table 5.10. Specific Resistance to Monoaxial Compression on Stabilized Ground Samples Under Frost - Thaw Cycles

ample code	Specific resistance to uncorrected average monoaxial compression		Raport h/d	Correction Factor (BS 1881, Part 120)	Specific Resistance to Average Corrected Monoaxial Compression	
	(σ, N/mm^2)	(σ, kPa)			(σ, N/mm^2)	(σ, kPa)
P Stabilized earth subjected to freeze-thaw cycles						
P1-FT	0,617	617	0,87	1,26	0,531	531
P2-FT	0,555	555	0,90	1,40	0,488	488
P3-FT	0,785	785	0,88	1,30	0,688	688
P4-FT	1,530	1530	0,88	1,30	1,327	1327
PN-FT	0,149	149	0,87	1,25	0,129	129

Here are some samples examined in Figure 5.2

Figure 5.2. Representation of the examined samples [48, 49, 50]

Taking into consideration the values of the resistance characteristics obtained for the blank samples and for the samples subjected to freeze - thaw cycles, there is an increase in frost - thaw compressive strength (except for natural ground samples where a decrease in resistance is observed) , calculated with relations: [130]

$$\Delta R = \frac{R_{FT} - R_m}{R_{FT}} \cdot 100$$

where: R_m - resistance to compression of thermally untreated stabilized earth specimens;

ΔR_{FT}- compression resistance of stabilized earth samples subjected to freeze-thaw

By reference to stabilized soil specimens exposed to freeze-thaw cycles, there is a observed a pronounced trend of significant and uniform 43-55% increase in the resistance characteristics for samples taken from lot 1 and lot 2, respectively 72-75% for those corresponding to lot A / B.

The exception is the natural soil sample, which shows a frost-thaw sensitivity - thawing by decreasing resistance by 32%. It can be concluded that stabilized land with enzyme products subjected to successive freeze-thaw cycles is highly stable. [130]

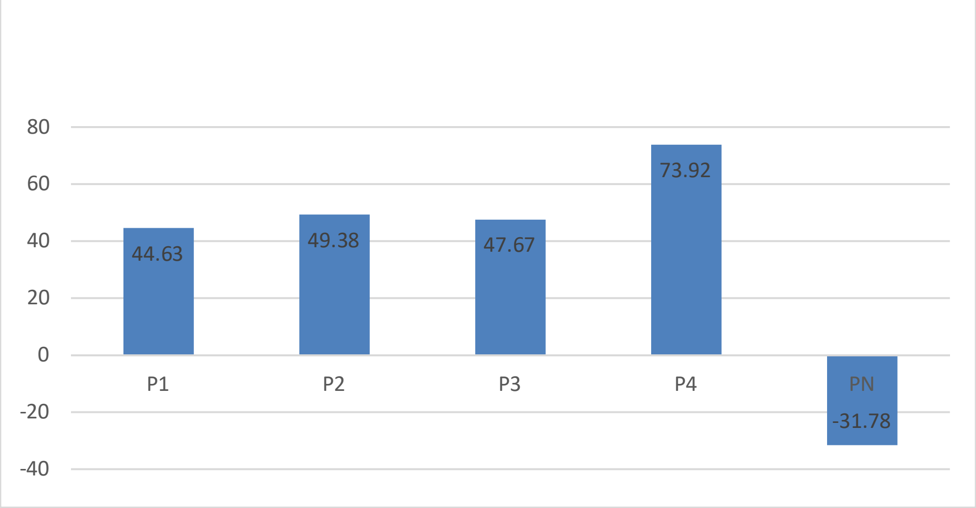


Figure 5.3. Graphic representation of increase in compressive strength after freeze-thaw

„ Determination of permeability in the laboratory”, SR 1913/6-76 „ Foundation soil.

Table 5.11. Determination of permeability in the laboratory.

No.	Sample Code	Hydraulic gradient (i)	Permeability coefficient k$_t$ (cm/s)
1.	LOT1-S2	16,52	8,11E-09
		14,78	7,69E-09
		11,30	7,07E-09
			7,62E-09

Identifying the method used: PTE-GFC-07 „ Determination of compaction characteristics. Proctor test” (modified Proctor test), SR 1913/13-83 „Foundation soil. Determination of compaction characteristics. Proctor test”

Table 5.12. The characteristics of the analyzed samples

Characteristics	Units of measure	Test number					
		1	2	3	4	5	6
The mass of the cylinder and the material, m_1	g	7800,4	7978,5	8128,2	8245,6	8197,2	8120,8
Mass of the empty cylinder m_2	g	3681,9	3681,9	3681,9	3681,9	3681,9	3681,9
The mass of material, m_m	g	4118,46	4296,6	4446,3	4563,7	4515,3	4438,9
Volume of compacted material, V	cm^3	2122,03	2122,03	2122,03	2122,03	2122,03	2122,03
Density $\rho = \frac{m_m}{V}$	g/cm^3	1,94	2,02	2,10	2,15	2,13	2,09
Average humidity, w	%	7,23	9,08	10,52	**12,01**	13,75	15,06
Density in a dry state$\rho_d = \frac{\rho}{1+\frac{w}{100}\cdot\rho_s}$	g/cm^3	1,81	1,86	1,90	**1,92**	1,87	1,82

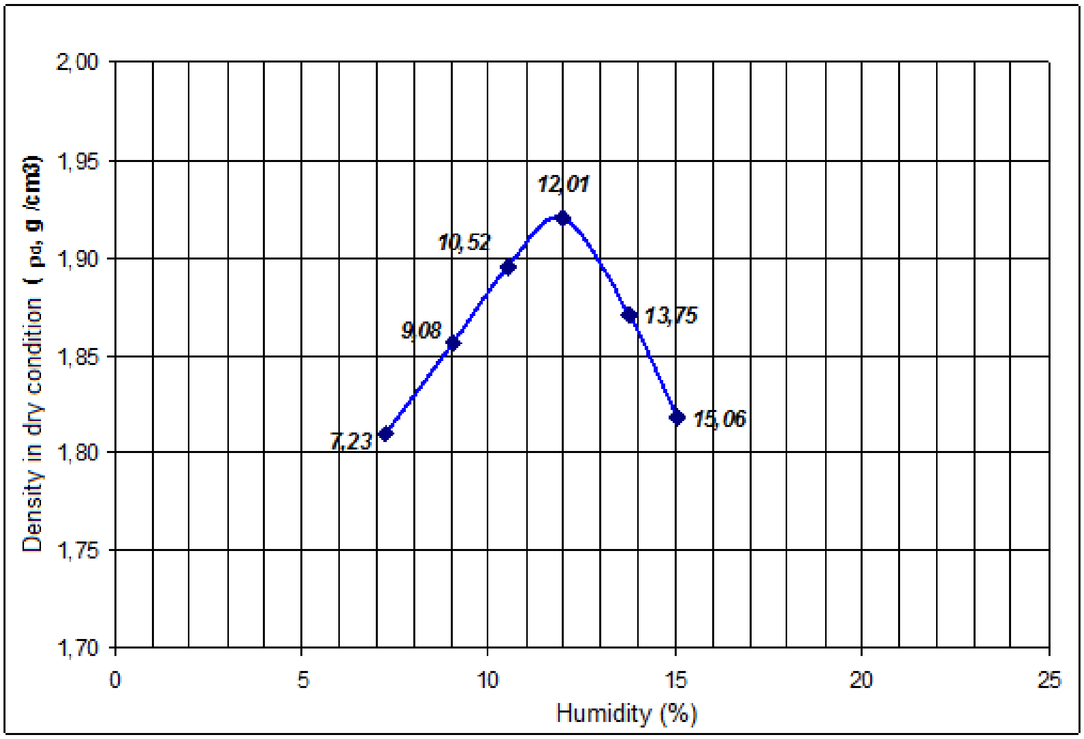


Figure 5.4. Testing a test with Proctor modified

5.4. Interpretation of experimental results

The experiments performed not only “in situ”, but also in the laboratory, aimed to highlight the modification of the parameters of deformability, elasticity and resistance of grounds stabilized with enzymes, based on a permanent procedure, comparative to the same grounds untreated with enzyme stabilizers, that is in the natural state.

- The modulus of longitudinal elasticity E_z determined at the request of axial compression, according to relation 5,6, for stabilized grounds, was evaluated for 1500 samples collected from the layer of stabilized ground for six mass doses ε of stabilizer, as results from

Table 5.2. It is found that as the percentage quantity of stabilizer ε increases, also increases the modulus E_z.

- The coefficient of Poisson, experimentally determined based on relation 5,7, for stabilized grounds, in the percentage quantities ε of the stabilizer, it is found to be increasing according to Table 5.3.
- The volumetric modulus E_v depends not only on the coefficient of Poisson, but also by the modulus E_z. Therefore, as the modulus of Poison and the dosage of stabilizer increases, it is found a pronounced increase of the volumetric modulus, according to the date from Table 5.4.
- The Californian index CBR, with the experimental results from Table 5.6, points out values correlated with the volumetric modulus E_v, being mentioned the fact that the values for the ground stabilized are 3 – 4 or greater than the case of ground untreated with enzyme solutions.

5.5. Conclusions.

The issue of stabilizing grounds with enzymes is made as an efficient opportunity for achieving the road structures by processing “in situ” of local grounds, improved with mineral aggregates and treated with organic substances.

In this context, is also inscribed the present work which shows not only the theoretical aspect of modifying the elasticity modulus by increasing the coefficient of Poisson, depending on the dose of stabilizer, as well as the experimental results obtained “in situ” on the polygon testing and in the laboratory.

It is mentioned the fact that were achieved experimental stages “in situ” with equipment of milling, mixture and atomization of stabilizer, the deposit of layers of unprocessed ground as well as the dynamic compaction through vibration.

The experiments consisted of sampling the natural ground and the layers of stabilized ground. Also, the dynamic charges from the field permitted the determination of the elastic moduli and rigidities. The capacity of resistance to road structure was measured “in situ” by determining the Californian index CBR:

Based on analytical and experimental results the following conclusions can be summarized:

- The enzyme stabilizers in atomized and homogenous mixture with the natural ground determine the significant modification of resistance, of volumetric elastic modulus, of coefficient of Poisson and of Californian index CBR;
- The presence of stabilizer with enzymes in the porous structure of grounds leads to significant increases of the modulus and of the Californian index.

Therefore, the ecological treatment with enzymes to earth assure the achievement of to road layers from ground with special performances.

CHAPTER VI

Conclusions, personal contributions and general directions of investigation

6.1. Conclusion

The problem of stabilization of enzyme soils is constituted as an effective opportunity for the construction of road structures by "in situ" processing of local soils, improved with mineral aggregates and treated with organic binders.

In this context, this work also make part of it, emphasizing at the same time the theoretical aspect of modification of elasticity model through increasing of Poisson coefficient, depending of stabilizer doze, and the experimental results obtained „in situ" on the training polygon and in laboratory.

It is mentioned that "in situ" experimental stages were carried out with milling, stirring and atomizing equipment of the stabilizer, the deposition of processed earth layers and dynamic vibration compacting.

The experiments consisted in sampling of natural soil and stabilized earth layers. Dynamic field loads have also determined the elastic and stiffness modulus. The strength of the road structure was measured "in situ" by determination of the Californian CBR index:

Based on the analytical and experimental results, the following conclusions can be summarized:

- the enzyme stabilizers in atomised and homogeneous mixture with the natural soil determines the significant change in resistance, of the volumic elastic modulus, of the Poisson coefficient and of the CBR californian index;
- the presence of the stabilizer with enzymes in the porous structure of the soil leads to a significant increase of the Californian mode and index.

The fundamental contribution of the doctoral thesis consists in the development by the author of a unitary and coherent analysis concept for the study of the roller-field interaction according to the elastic, dissipative and plastic characteristics of the analyzed media as well as the dynamic behavior of the considered structural and functional assembly.

a) The thesis emphasizes the need to develop and implement new rheological models for stabilized soils and of some dynamic models suitable for obtaining information as close as possible to reality. Therefore, a comparative analysis of the behavior in static regime, but especially in the dynamic regime of compaction equipment to interaction with the ground based on physical, numerical, rheological and virtual models has been performed. Have been developed models with multiple degrees of freedom of a vibrating roller and also were analyzed rheological models for different types of land (poor cohesive or cohesive).

b) "In-situ" instrumental tests complemented with a series of experimental laboratory tests have provided a database (underlying a systemic plan of multi-correlation analysis) that was effective in the numerical and virtual simulation process of vibratory roller - ground system. Thus, this database is very beneficial to the behavioral harmonization processes and with parametric assignment of the mathematical/numerical models provided with the identifiable and measurable reality of the given phenomena.

c) The numerical results and virtual scenarios have contributed to substantiating of the set of essential requirements for assessing the ground response and of the condition of demand induced by the technological equipment.

d) the establishment and substantiation of the concept of validation of the set of proposed interface models in relation to the assessment of the level of performance imposed on the final compacting degree led to the validation of the models. The parameterized character of their design ensures the modeling of different types of land, the number of passes, layer thicknesses and the individualization of each compaction equipment used.

e) The complex simulation of the cumulative effect caused by successive passes and depth assessment of the compaction degree across the area of interest by estimating of actual dynamics and scaling it over the entire area being monitored.

f) the establishing of parametric performance correlations.

The large volume of works, including the process of compaction and control of the achieved results, which characterize the achievement of constructions from local materials, requires the involvement of the most efficient execution technologies, which in an efficient manner determines the qualities required for the materials by the fitting functions concerned.

The influence of water content in the compaction process, particularly carried out by plain vibratory rollers, is generally demonstrated and recognized in the specialty literature. The various compaction test results, presented mainly by the density in dry condition-water content relationship, show the major effect produced by this parameter on the degree of compaction achieved in compacting of fine granular soils. However, there is not enough information available in the literature to develop general expressions that might be useful in predicting the practical results of compaction works. To achieve a compacting level corresponding to a specific type of soil, these equations indicate the required number of passes of the compacting machine depending on its type and the water content of the compacted material. Unfortunately, even if those expressions are based on tests carried out on different types of machinery, it seems that the lack of clear information makes their application uncertain.

The analytically determined response for the compacted material system - vibratory cylinder system shows that the variation in water content has an important effect on the vertical displacement of the cylinder, and consequently on the energy absorbed by the material.

The numerical analysis by means of the finite elements of the behavior of the vibratory cylinder system - compacted material system has led to results that tend to follow generally the analytically determined response.

The main result retained by the analysis was the displacement on the vertical soil in its contact area with the cylinder, this size being chosen as a comparison with the results obtained through the analytical study. It has been found that, when the natural oscillation frequency of the cylinder is not approaching of the vibratory operating frequency, the results obtained by the numerical analysis show the intended arrangement, and thus the modeling and the analytical procedure, although perfect, are still appropriate. On the other hand, given that in the case when the mentioned natural frequency equals the operating frequency, the curve of the numerically determined displacements no longer presents the corresponding altitude, means that the dynamic load modeling, respectively the applied analysis procedure, are deficient.

6.2. Personal contributions

The personal contributions that come from the entire investigation activity and presented in the doctoral thesis note that the general objective of the doctoral activity of elaboration of a set of applicative models, monitoring, functional parametric control, equipment and material interface, as well as performance analyzes can be synthesized as follows:

a) Synthesis and classification at the level of performance of the relevant national and international achievements in the field of compacting with vibrations of soils;

b) Establishment of rheological models for the purpose of implementation in specialized instrumental and computer systems for simulating vibration-soil roller interaction at the compaction process;

c) Dynamic behavioral analysis of rheological models for highlighting of specific parameters in relation with their ability to realistically describe the compaction process;

d) Conceiving, developing and substantiating of the proposed models, taking into account the plastic, elastic and dissipative characteristics of the studied soil and the dynamic behavior of the structural and functional assembly examined. Thus, the necesity for modeling of soils stabilized with additives such as bitumen, ash, cement, enzymes is mentioned.

e) Functional correlation of the inertial, conservative and dissipative elements, in order to optimize, the parameters of performance, highlighted by the efficiency of the compaction given by the force transmitted to the soil.

f) Creation of a research program of “in situ” experimental results supplemented by a series of experimental laboratory tests to highlight the influence of some functional, constructive and technological parameters of the compactor on the degree of compaction;
g) the conception of some functional laws between the parameters describing soil evolution (non-cohesive, poor cohesive and ballast) in the compaction process;
h) Establishment of performance parameters in the compacting process of road structures.

6.3. Future investigation directions

The obtained results, the hypotheses and the studies in the thesis are meant to suggest the following research directions in the future, such as:

- Development of some performance models based on complex nonlinear models of variation toward the constitutive parameters involved in the compaction process;
- Ensuring accurate measurement of monitored parameters during compaction with the use of high tech measuring devices/systems that allow real-time data recording and variation;
- Achievement of a device /system /apparatus which will monitor in real time, that would store and process the variation of significant parameters in the compaction process, the possibility to automate the “in-situ” adjustment / control process and machine working characteristics depending on the soil response;
- the conception of an electrical and computer device to determine the cumulative effect of performance in the process of compacting with technical and economic decision.

As a result, it is mentioned that the field of dynamic behavior is complex through the variety of materials, of dynamic equipments and instrumental methods that are still performing and remains open to continuous research in order to achieve the efficiency and quality of the construction of road structures.

The insuring of an appropriate system to determine the degree of real-time compaction to cohesive, poorly cohesive soils stabilized with natural organic compounds of the enzyme type.

In the future, a varied evolution of soil stabilization for road structures is estimated using chemical or organic feed materials.

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