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DYNAMIC SIMULATION OF THE VIBRATORY ROLLER – TERRAIN INTERACTION USING AN ELASTO-PLASTIC APPROACH

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ABSTRACT

This study deals with the problematic of deep interaction between the terrain and the vibratory drum at the technological process of dynamic compaction. In this paper is briefly presented a theoretical approach of this dynamic phenomenon based on a set of conservative and frictional dissipative rheological models. Simulation results reveal proper evolution of the numerical models comparative with the real systems behavior. Hereby, timed evolutions of both elastic and consolidation stages, in strength linkage with vibration parameters and terrain characteristics, enable the algorithmic developing of the interaction characteristics in terms of technological equipment and processed material.

KEYWORDS: vibratory compaction, rheology, dynamic simulation, elastic model, frictional dissipative model

1. INTRODUCTION

Virtual simulation model of vibratory roller-field system behavior must take into account both the characteristics of the two basic elements - body work and field respectively, and the interaction between them. The basic element of this analysis is the rheological model which is able to simulate the phenomena occurring at the interface between roller and terrain.

In Figure 1 are presented four rheological models based on elastic and dissipative behavior, capable of simulating the behavior of the terrain interacting with the body work of vibratory compaction equipment.

These two models are elasto-plastic type without consolidation (a) and with the consolidation (b). The specific settlement of material types can be modeled by each of the two rheological models, but the consolidation phenomenon is simulated only when that two components are installed in parallel (see Figure 1.b).

Taking account the theoretical considerations it is proposed that the initial version for an application development intended to simulations on the virtual model of complex system behavior roller - terrain a dissipative elastic model of the type shown in Figure 1 (b).

The reasoning behind this approach consists of the following aspects:

- This model is simple interms of structural view and functionally, providing an easy way of implementation within a numerical simulator;
- The proposed model is able to highlight the feature of strengthening the materials;
- The absence of dissipative components by the viscous type, which although in some cases may be a weakness of the model, removes restrictions relating to the application speed of external loads and thus it is gained a general model relative to the type and method of excitation.

The constitutive equation of elastio-plastic model in Figure 2 is

$$F_{ex} = \begin{cases} k\,x(t) + F_{fr}\ sign\left(\frac{dx}{dt}\right) & pentru \quad F_{externa} > F_{fr} \\ 0 & pentru \quad F_{externa} \le F_{fr} \end{cases} \qquad (1)$$

where k is the stiffness of the elastic component F_e of the model, F_{fr} is friction force of the specific plastic component F_p and *sign* signifies *signum* function.

In this model the friction force is the Coulomb type, that is a constant evolution with the speed.

The behavior of elasto-plastic model consolidation (see Fig.2) under external load σ is summarized in Table 1.

This model is nonlinear because of the presence of an element that simulates Coulomb friction type. The solving of this type of mathematical model involves the use of specific numerical methods for approximating the final solution or model implementation within a software package specializing in computerized maths. This second option is preferable because it assumes the existence of computational routines optimized and adapted to a wide range of types of mathematical models. Thus is eliminated the verification stage of mathematical model relating the way and the accuracy of the final solution evaluation.

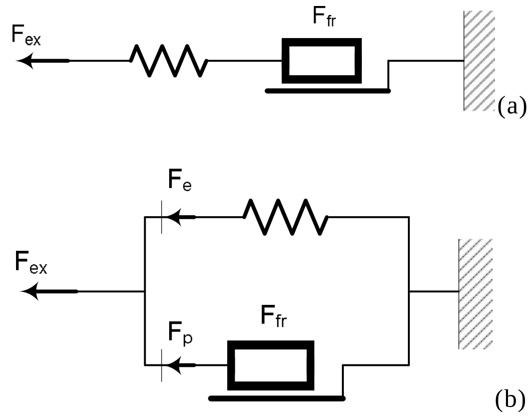


Fig. 1. Rheological models for simulation in the field interacting with vibratory compact equipment; a) elastic and plastic model without consolidation; (b) elastic and plastic model with consolidation.

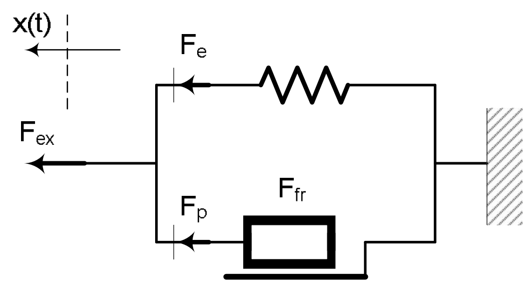


Fig. 2. Elastic and plastic model for simulation analysis terrain behavior in interaction with vibratory compactor equipment

Table 1. Numerical behaviour of working of elasto-plastic model with consolidation

INTERNAL CONDITIONING		EXTERNAL CONDITIONING	
		$\sigma \le F_{ex}$	$\sigma > F_{ex}$
$F_e \le F_p$	solution	$x_i = x_{i-1}$	$x_i = \sigma / k$
	state	*null deformation*	*elasto-plastic deformation*
$F_e > F_p$	solution	$x_i = F_p / k$	$x_i = \sigma / k$
	state	*elastic recovery*	*elasto-plastic deformation*

Therefore, to solve the proposed model it has been adopted a variant of mathematical applications in computerized environment Matlab ©. From the vast library of functions, routines and specialized modules of available computing solution implementation in Matlab was chosen a rheological model, a type application Simulink © - SimMechanics ©. The main advantages of this approach are given by the following:

1) the module of programming is of graphical type, removing in totality the writing stage orders related to the application;
2) the existance within the Simulink © - SimMechanics © of functional elements readily programmed (verified and optimized) that perform different tasks in order to reduce the use of the application programming specific elements and the establishment of interconnections between them.

2. NUMERICAL SIMULATION

In Figure 3 is presented the basic scheme of the application for the analysis of elasto-plastic model behavior with consolidation (see Fig. 2) subjected a harmonic type of external actions.

It makes mention that the type of excitation may change depending on the requirements analysis problem by simply replacing the corresponding element of the scheme (in the case presented "Sine Wave" - Harmonic signal generator) and setting the working parameters.

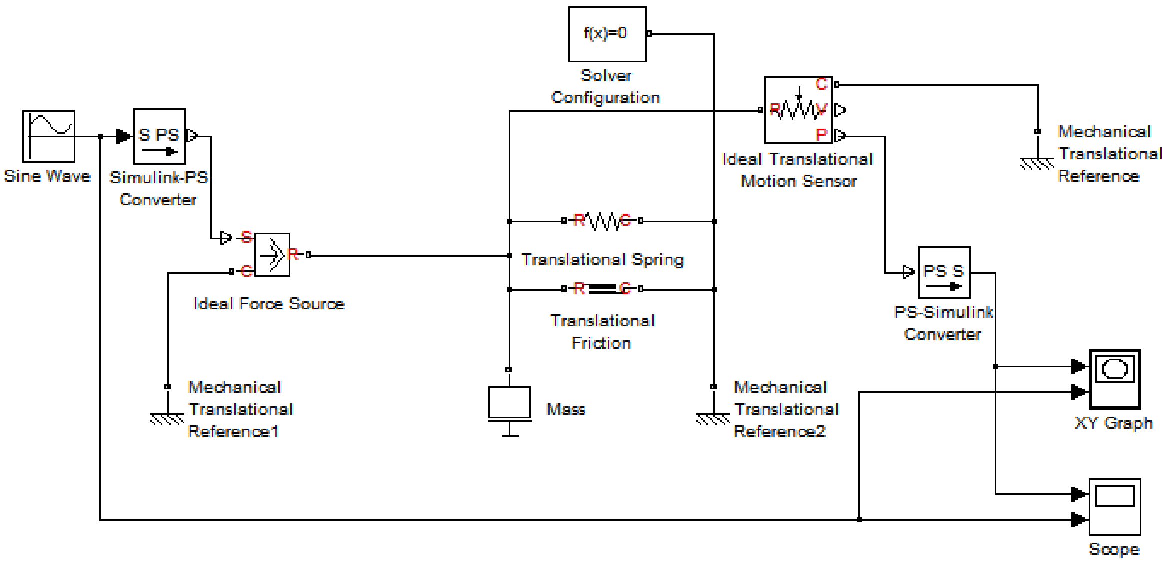


Fig. 3. The Basic scheme of the virtual instrument model analysis of elastio-plastic behavior of the harmonic actions

Constituent elements of the diagram shown in Figure 3 are characteristic of applications in Simulink © - SimMechanics ©. Per categories, these are:

1. the elements of signal generation (Sine Wave),
2. takeover elements, Graphic presentation and plotting aid of the results (XY Graph, Scope),
3. signal conversion elements from Simulink in SimMechanics (Simulink-PS Converter) and backwards (PS-Simulink Converter),
4. excitation elements (Ideal Force Source),
5. transducers elements for retrieving information from different points of interest in the analyzed scheme (Ideal Translational Motion Sensor),
6. the basic elements of the application which simulates the rheological behavior of the model proposed (Translational Spring - linear elastic element, Translational Friction - dissipative friction element, Mass - element type moving mass of translational, Mechanical Translational Reference - reference point which materialized fixed link to the global coordinate system),
7. the block for setting parameters needed for numerically solving to the specific mathematical model of the set of equations (Solver Configuration).

In general, there are two major categories of functional blocks, namely: those that contain the basic elements and those containing auxiliary elements necessary to assemble and execute the application. The basic elements are those that ensure the implementation of the characteristics required for the desired pattern.

In the case presented in Figure 3 these elements are:

- the linear elastic element - this implements a constitutive Hooke law which entails a linear dependence between deformation element and forces applied at its extremities; the element requires initial determination of stiffness coefficient and unit of measure for this.
- the dissipative friction element - this is a nonlinear element and implementation available in Simulink © - ©

SimMechanics allows programming of complex and general laws, which contain data regarding the static, dynamic and viscous frictions. General law is of the form

$$F = \left[F_C + \left(F_{brk} - F_C\right) e^{-c_v |v|}\right] sign(v) + f_v\, v \quad (2)$$

where notations have the following meanings:

- F is the total friction force, simulated by the respective element,
- F_C is the Coulomb friction force which involves a constant value independent of the external load application speed,
- F_{brk} is the force of static friction (at detachment) - this value is a threshold value and is valid for null speed load application,
- c_v is a coefficient of proportionality, the corresponding model of Stribeck friction law which requires an emphasized decline at the value of the friction force depending on the load application speed,
- $v = v_R$-v_C is the relative velocity between the two points of connection of the model (R, respectively C, on the diagram in Fig. 3)
- f_v is the viscous friction coefficient, which defines the proportionality between the friction force and the external load application velocity.

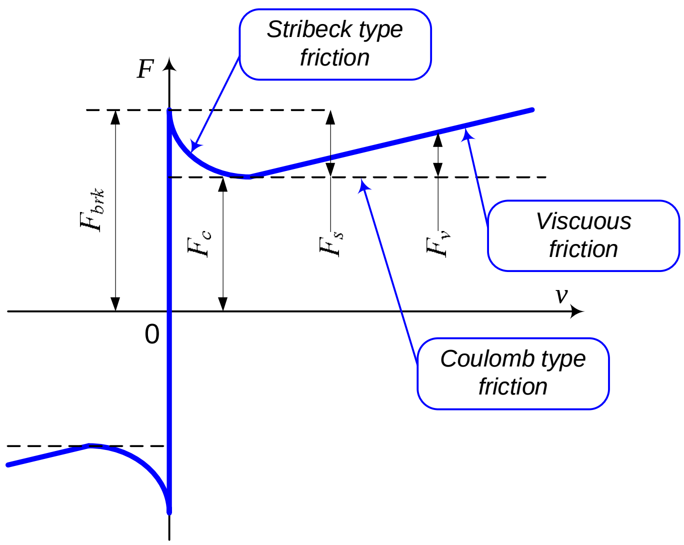


Fig. 4. The complex model of the friction force-theoretic version (implemented in Matlab-SimMechanics© software)

In Figure 4 is presented the corresponding grafic variation law of the friction force - equation (2). The diagram in figure 4 shows the three characteristic areas described in the previous paragraph. It can be noticed also that for null velocity values the characteristic is discontinuous. This fact is due to the specific threshold value of static friction. In this case the approximation is purely theoretical and has some major inconvenience. Among these are mentioned the following:

- special problems occur in the numerical solving of the model due to the existence of the discontinuity point
- the respective simplification is not a realistic approach in the sense that the phenomenon of discontinuous friction model does not have cover into reality and mechanical contact with the mass distributed model does not ensure the instantaneous increase of the friction force developed.

In the specialty literature there are many types of models of the phenomenon of friction without discontinuities. In the module implemented in Simulink © - © SimMechanics has been adopted a simple model of the friction force that ensures continuity depending on the relative speed of application of the external request. Mathematics formulation (3) is the characteristic equation of this model. In Figure 5 is shown the diagram corresponding to this type of continuous model.

$$F = \begin{cases} \left[F_C + (F_{brk} - F_C)e^{-c_v|v|}\right] sign(v) + f_v\, v & pentru \quad |v| \geq v_{th} \\ v\,\dfrac{f_v\, v_{th} + \left[F_C + (F_{brk} - F_C)e^{-c_v v_{th}}\right]}{v_{th}} & pentru \quad |v| < v_{th} \end{cases} \quad (3)$$

The novelty element compared with to previous model - equation (2) and Fig. 4 is represented by the elimination of origin by introducing a discontinuity finite and very narrow areas, near the origin. It is considered that the friction force is proportional to speed.

3. ACHIEVED RESULTS. DISCUSSIONS

For modeling the interaction between the roller and terrain within the numerical applications presented in Figure 3, was adopted a type of harmonic excitation force. The simulation of the static component of the total force applied on terrain uses an additive constant on the expression of the dynamic component. Thus, the approximation relation of total excitation force is

$$F_{ex}(t) = F_{st} + F_{din}(t) = F_{st} + A_o \sin(\omega\, t + \varphi) \quad (4)$$

where F_{st} is the static component, F_{din} is the dynamic component, A_o is the amplitude of the dynamic component, also ω end φ are the pulsation, respectively the phase shift at the harmonic excitation. The simulation of continuous pressing on the soil no matter their dynamic working conditions imposes the static component value to be higher than the peak to peak amplitude of the dynamic component.

For the case presented in the paper were adopted the following excitation source parameter values F_{st} = 26 N, A_o = 25 N, ω = 2 rad/s, φ = 0°. The corresponding diagram is given in Figure 5. The considered system response at harmonic excitation in Figure 5 is shown in Figure 6. In this figure are shown both the total deformation terrain diagram (a) and a detail of the area compaction (b).

In the diagram from Figure 6 are marked the two work areas of interest, namely: the elasto-plastic area where the material is compacted and respectively the elastic area in which the material takes the form of external dynamic loads exclusively of some elastic deformations in successive cycles loading - unloading without the presence of remanent deformations. Basically this area corresponds to both the consolidation regime post-compaction and effective regime of exploitation. With ε_p was labeled the total plastic deformation (consolidation is C_t) and the elastic deformation with ε_e is produced by dynamic loads disturbing.

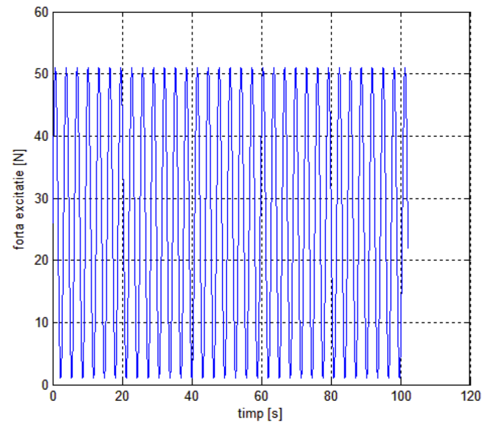
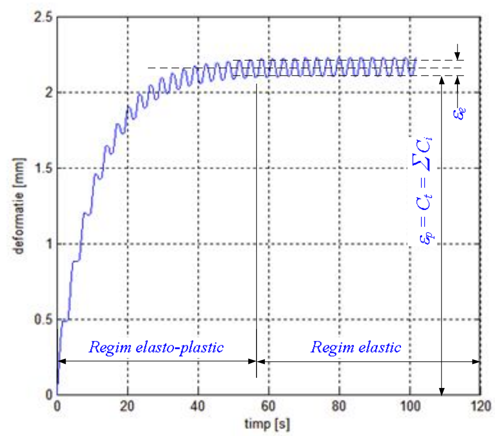
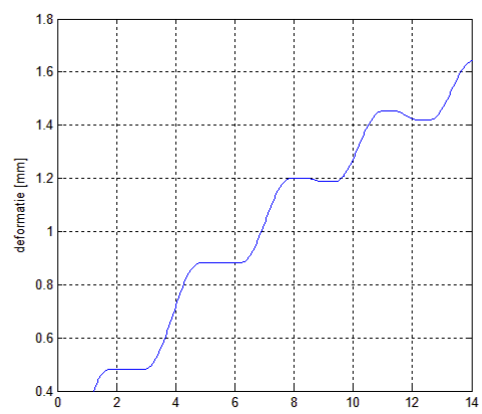


Fig.5. Excitation signal - harmonic function



(a)



(b)

Fig.6. The system response at harmonic excitation function from Figure 5.
(a) Highlighting the working regimes and essential parameters of vibrating compaction process during about 100 s; (b) detail.

4. CONCLUSIONS

The proposed model for the analysis of system behavior vibratory roller - terrain started from a principal hypothesis according to which for the development of complex virtual instrument required for depth analysis of the proposed issues it is absolutely necessary to give a first numerical approximation to be able to simulate the essence of the phenomenon of interaction between machine and terrain.

For achieving a complete model for the analysis of system behavior vibratory roller – terrain it is necessary to provide a model for basis (a nucleus, a first approximation of the model) which has the following characteristics:

- to be simple enough to be easily understood and solved;
- to be sufficiently complex to simulate the essential phenomena to be analyzed.

The aim of this study was to determine and verify such a basic model that can simulate the compaction process of the terrain under the action of dynamic loads produced by a vibrating roller compactor.

Analyzing the results presented earlier in the paper and considering the hypothesis stated above, one can conclude that the initial purpose was reached and elastic-plastic model with consolidation is the best solution to simulate the compaction process.

The achieved application highlights all the important aspects of the interaction roller vibrator with the terrain that must be compacted. The application will be developed further by including aspects of the nonlinear behavior of the terrain, the change in real-time excitation parameters and influence of the state on the effective range of adjacent areas analyzed.

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