Natural adaptation of deformable work tools during vibratory soil compaction and enhancement of there performance.

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Abstract. The issue discussed in the article is natural adaptation of working tools of road compactors as well as the use of that property for enhancement of soil compaction. There are well known technical solutions concerning forced adaptation of pneumatic tyres. The article deals with the problem of natural adaptation for hydraulic tyres. Their elastic and viscous properties may be naturally changed according to change in mechanical properties of compacted soil in order to enhance their performance and increase energy efficiency. The article represents consideration of special sectioned hydraulic tyre design which allows deformational properties of the tyre to accommodate according to strengthened soil during compaction.

1. Introduction
Innovative technical solutions and machines for soil compaction is one of promising ways for enhancement of performance and productivity in construction industry. Improvement of efficiency of soil compaction demands for solution of different types of problems. The main problem to be solved for the efficient compaction is the problem of adaptive control of surface force acting on the soil. It must be done the way which cause the largest possible amount of the soil that is interacting with work tool to retain the stressed state that makes it deformation as plastic as possible without destruction. This is correct also for the vibratory rollers being nowadays the most widespread mean of soil compaction. Transition to the intelligent soil compaction [1] is provided by the adaptation of parameters of surface action on the soil – contact pressure at the first place. The tools for that are given by the methods of automatic control and regulation for compaction which allow to change necessary way the entire variety of accessible parameters of surface force and working regime of the roller [2, 3]. Deformable work tools represent the subject of special interest for the research. Especially it refers to the work tools which can demonstrate adaptation either enforced or natural. In any case adaptation results in variation of surface force, mainly periodic, which must correspond to the properties of the soil which change crucially as the compaction proceeds [4]. Among deformable work tools – pneumatic and hydraulic tyres, the last show decent efficacy for the compaction of road materials which admit the variation of deformational properties in wide range depending on the stage of compaction [5]. Anyhow for compaction of soil materials hydraulic tyres require use of additional pieces of desing [6].

2. Formulation of the problem
Hydraulic work tools of vibratory rollers are not ultimately suitable for compaction of entire variety of soils used for construction purposes. The problem stated in the article is to work out innovative design
of hydraulic tyre in order to improve the range of its applications for soil compaction. Additional mechanisms of natural adaptation of deformational properties is going to be used for that purposes.

3. Theory

The basics of theory for construction of deformable work tools belong to the field of contact problems for elastoviscoplastic media. For practical purposes, anyway, this way of consideration appears to be excessively detailed. Quasistationary regimes of compaction may be described from the point of lumped parameters approach to the problem of interaction of roller’s deformable work tool and active region soil layer [7]. This approach was implied during construction work tool with forced adaptation of stiffness of pneumatic tyres [4]. In the framework of lumped parameters model one can represent the motion of roller’s suspension attached to the drum possessing the viscous and elastic properties under the time-dependent force $F(t)$ (Fig. 1).

![Model representation of work tool interaction with soil (suspension included)](image)

**Figure 1.** Model representation of work tool interaction with soil (suspension included)

Damping of energy in work tool calls for consideration of the soil as a “black box” which influences the interaction by nonlinear dependence of viscosity and stiffness of the work tool on position of the center of mass in respect to soil surface. For small deformations and stiff work tools these nonlinear dependences may be neglected but for deformable work tools play significant role. Relatively large deformations of hydraulic tyres and pneumatic tyres restrict their use for compaction of cohesive soils due to high rate of energy loss as well as for compaction at high relative densities. Use of deformable work tools generates additional problem of control for dissipative properties of both soil and work tool. That demands for minimization of energy dissipation during compaction in order to achieve optimal energy efficient working regime of the roller. It also must be taken into account that energy losses may be caused by processes which are not connected with internal friction. Influence of dissipative properties of pneumatic tyre with controlled stiffness on quality of energy transmission to soil media was investigated in [8]. The problem of great interest here represent processes of energy dissipation in soils of ground fills under compacting action. In works [3,10] connection between parameters of external force and efficiency of soil compaction was determined.
Energy balance for interaction process may be written down as (we consider work tool absolutely elastic)

\[ E = E_{\text{diss}}^{\text{WT}}(c_{\text{WT}}, b_{\text{WT}}, F_0, \nu) + E_{\text{diss}}^{\text{soil}}(c_{\text{soil}}, b_{\text{soil}}, F_0, \nu) + E_{\text{def}}^{\text{WT}}(c_{\text{WT}}, b_{\text{WT}}, F_0, \nu) + E_{\text{def}}^{\text{soil}}(c_{\text{soil}}, b_{\text{soil}}, F_0, \nu), \]  

where \( E_{\text{diss}}^{\text{WT}}, E_{\text{diss}}^{\text{soil}} \) is energy which goes for work of dissipative forces during deformation of work tool and soil respectively; \( E_{\text{def}}^{\text{WT}}, E_{\text{def}}^{\text{soil}} \) are energies of deformation (including plastic part) of work tool and soil respectively;

\( F_0, \nu \) are amplitude and linear frequency of external periodic force;

\( c_{\text{WT}}, b_{\text{WT}} \) and \( c_{\text{soil}}, b_{\text{soil}} \) represent stiffness and viscosity of work tool and soil respectively under the formalism of lumped parameters approach.

It must be mentioned that elastic and viscous characteristics of both work tools and soil in arbitrary case are non-linear in respect to deformation as well as they depend on the value of plastic deformation of soil and value of area of contact spot which determines the size and shape of part of the soil layer which is involved in interaction at the moment of time. Energy efficient compaction pattern of work tool adaptation may be qualified as the one which causes the least possible damping in the work tool – which means minimization of the first member in (1).

System of equations depicting the motion of mechanical system «frame – work tools» can be written as

\[ m_{\text{WT}} \ddot{z}_{\text{WT}} = -c_{\text{WT}} (z_{\text{WT}} - \dot{z}_{\text{WT}}) - \dot{b}_{\text{WT}} (\dot{z}_{\text{WT}} - \ddot{z}_{\text{WT}}) + F_{\text{ext}}(t) \]

\[ m_{\text{soil}} \ddot{z}_{\text{soil}} = -c_{\text{soil}} (z_{\text{soil}} - \dot{z}_{\text{soil}}) - \dot{b}_{\text{soil}} (\dot{z}_{\text{soil}} - \ddot{z}_{\text{soil}} - \ddot{t}) \]

Here we assume that stiffness \( c_{\text{soil}} \) and viscosity of \( b_{\text{soil}} \) suspension of the roller are constant and stiffness and viscosity of the work tool depend on the deformation parametrized in respect to the surface of the soil. Deformation of the soil is not considered explicitly but it is taken to the account in nonlinear dependences of viscosity and stiffness of the work tool on deformations.

Here we represent innovative design of hydraulic tyre work tool which was patented according to [10] and may be classified as a piece of machinery designed to produce surface action on soils of different types during compaction. Vibratory rollers traditionally used for compaction of materials of ground fills and dams can provide different patterns of dynamic action on soil layer. Work tools of the rollers also vary in shape size and mass and can be classified as smooth, grid, pad-and sheepfoot. Special place here belongs to deformable drums usually presented by pneumo – and hydro – tyres. Deformative properties of such work tools may be regulated and controlled enforcing way or naturally basically by the reaction forces which occur during the interaction with soil layer.

There are similar constructions for instance patented road roller drum [6] which consists of drum and vibratory exciter drives, tyre, vibratory exciter and gear mechanism. Drum consists of elastic tyres filled with water. The low energy transmission efficiency to the soil of given design at the high relative frequencies of the soil when the material achieves certain strength is a principal drawback of the construction. The reason for that is growing deformations and accompanying oscillations of high amplitudes of viscous liquid interior (uncompressible) of the tyre. This fact obviously lowers efficiency of compaction and since that output of the roller.

Below we suggest new design of hydraulic tyre drum which definitely improves performance of that type of rollers. This result is achieved by introducing sectioning elements which isolate parts of the interior of the tyre with ability to isolate the part of liquid which interacts with the soil at the given moment without redistribution of the liquid. This causes increased stiffness of the drum and decreases deformation which means higher contact pressures and in consequen, better further compaction.

The front and side cross-sections of the undeformed tire filled with liquid is presented on figure 1 (there is gap for free liquid redistribution between closing parts 3 and 4). Figure 2 represents deformed...
state of the tyre 2 with wedges 3 and 4 clenched. Since that sections of the tire are isolated from each other and deformational and viscous properties of entire tyre undergo sufficient change.

![Figure 2. Sectioned hydraulic tyre in initial state (undeformed)](image)

![Figure 3. Sectioned hydraulic tyre sectioned with closed gaps in situation of natural adaptation in respect to surface stress and damping](image)

Work tool consists of one or several hydraulic tyres 2 filled with liquid mounted on wheel 1. Interior volume of tyre 2 separated by pairs of wedges 3 and 4 with gap 5 between them, with wedge-like locks on their tops. Wedges are the parts of tyre 2 and are made of the same material.

If the deformations of the tyre are small then wedges 3 and 4 will not touch each other. In case of larger deformations of tyre 2 the gap 5 decreases and liquid of interior which tend to redistribute through it to other parts of tyre 2 produces force of resistance caused by viscous friction. Tis force increases with decrease of gap 5 and counterparts further deformation of the tyre which leads to constant value of contact area and cause lower rate of growth of contact pressure. Further growth of strength of soil deformation may achieve values when wedge like locks on wedges 3 and 4 completely close gap 5 and section will be separated from the rest of the tyre 2 as shown on Fig. 2. Wedge-like shape of wedges insures quality of locking and since that separation of sections.

Closing of gap 5 between wedges 3 and 4 decreases volume of liquid in tyre 2 interacting with the surface of soil layer and increases its stiffness with corresponding decrease of viscosity.
Adaptive elastic and viscous properties of tyre 2 depend on number of wedges 3 and 4 and initial size of gap 5. These parameters may be chosen the way to correspond the properties of soil being compacted. It will enhance performance of hydraulic tyre work tool of the roller and increase its output for all stages of compaction.

4. Results and discussion

Analytical consideration of system (2) for different cases were performed and values of viscosity and stiffness of tyre were obtained. Graphs of viscosity and stiffness of hydraulic tyre in dimensionless form are presented on figures 3 and 4. Variable \( x = \frac{z}{d} \) represents deformation of the tyre in respect to size of the gap 5.

\[ \frac{c}{c_0} \]

\[ \frac{b}{b_0} \]

Figure 4. Dependences of stiffness of the tyre depending on deformation (\( x = 1 \)) corresponds to the clenching of wedges for cases 1 - \( n = 6 \), 2 - \( n = 10 \), \( n = 16 \) pair of wedges respectively.

Figure 5. Dependences of viscosity of the tyre depending on deformation (\( x = 1 \)) corresponds to the clenching of wedges for cases 1 - \( n = 6 \), 2 - \( n = 10 \), \( n = 16 \) pair of wedges respectively.

Clenching of wedges causes growth of elastic and decrease of viscous properties for hydraulic tyre. This results in decrease of area of contact spot and consequently to the rise of contact pressure. That may be classified as a mechanism of natural adaptation of deformational properties of work tool in respect to enhanced strength of soil material under compaction.

The result of the complex approach to the design of promising hydraulic work tool for compactor is a construction of sectioned hydraulic tyre. It sufficiently broadens limits of use for hydraulic tyres in soil compaction. This is caused by:

1) Sufficient increase of stiffness for deformed tyre which realizes regime of natural adaptation in respect to contact pressure which is necessary for compaction of soils at high relative densities.
2) Decrease in viscosity which causes higher energy efficiency of compaction due to lower dissipation of energy in work tool.
3) Enhancement of moving properties of self-propelled hydraulic-tyred roller.

5. Conclusion

Sectioning of interior of hydraulic tyres as work tool of roller increases deformational properties and at the same time the ability for adaptation according to evolution of properties of soil media during
compaction. At the same time working properties of hydraulic tyres operating at regimes which do not lead to deformations necessary for overlapping of wedges 3 and 4 are retained. Sectioning does not prevent filling and emptying the tyre with working liquid if necessary. Improved hydraulic work tools are able to provide the range of contact pressures wide enough for compaction of soil media at all stages of compaction. This was possible because of implied mechanisms of natural adaptation in respect to contact pressure and dissipative properties which also leads to higher energy efficiency of compaction.

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