Theoretical research of soil packing by timber harvester running gear

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Abstract. The problem of ecological compatibility of self-propelled vehicles and soils is intricate and requires integrated systematic analysis of multiple tasks. This work is aimed at studying theoretical researches of soil packing caused by timber harvester running gear. To preserve and ensure faster restoration of forest soil fertility it is necessary to define at the cutting area development stage the tolerable limit of the timber harvesting equipment's impact at which soil disturbance does not become irreversible and the process of restoration of its properties is the shortest.

1. Introduction

Machinery impact on forest growth conditions and forest regeneration have been studied from the beginning of mechanization of logging operations up until recently. In due time those issues have been examined by Melekhov [1], Pobedinsky et al. [2], Kotikov [3], Klubnichkin et al. [4], Pirnazarov et al. [5]. The researches in question of non-rigid properties of soil affected by buildings’ and structures’ foundations as well as vehicle running gear have found out a variety of mathematical models describing compression and shearing deformation of soil. The rutting process researchers have been mainly conducted from the point of improvement of passability and tow properties of the vehicle and have given no ecological assessment of soil and ground state at logging areas.

The problem of ecological aftermaths of mechanized timber cutting raises a problem of development of theoretical foundations of forecasting of industrial factors’ impact on forest soils. At the stage of development of logging area it is necessary to decide upon timber-harvesting equipment and timber-harvesting technology to be used, providing for state of logging area soils not reaching limit values of the biological activity the case when soil damage is not irreversible.

2. Materials and methods

When a vehicle moves, a “core of packed soil” is formed under wheels or tracks in lateral section. This core reminds a wedge and is introduced into a bearing mass shearing away the soil on the sides. That is why general deformation which is a rut depth represents a sum of packing and shearing deformations.

Movement of skidders along skidding tracks is accompanied by accumulation of deformations thus causing deepening of rut depth Bottinelli et al. [6], Cambi et al. [7], Horn et al. [8], Klubnichkin et al. [9]. The number of vehicles’ trips along a track, depending on maximum load of running gear, type
and state of soil, leads either to weakening of rut depth growth rate, or vise versa to its progressive growth: in the first case the bearing mass features packing deformations, and in the second case, shearing deformations.

The energy conveyed to soil from a wheel or track is converted into soil deformation energy and is determined by the following formula.

\[ A = b \cdot S_d \int_0^{hk} q \cdot dh \]  

\[ A \] – rolling energy during the cycle time of soil loading by vehicle element running gear;  
\[ b \] – running gear width;  
\[ S_d \] – actual trip mileage for a specific period of time;  
\[ hk \] – full deformation (rut depth);  
\[ q \] – pressure.

The analysis of the above equation shows that in lack of slipping when actual trip \( S_d \) corresponds to length \( S_t \) of surface of contact between running gear and soil, expression (1) describes the energy required for pressing into soil a flat die having a width \( b \) and length \( S_t \) to the depth equal to rut depth.

The final objective of the search is to determine the degree of soil packing under vehicle’s impact. Let us take a process of rutting as a consecutive soil deformation by a flat die of the given size and use for mathematical description of that process the provisions of soil mechanics obtained basing on general theory of linear solids which assumes that deformation \( h \) varies in direct proportion to pressure \( q \), that is

\[ h = a \cdot q \]  

where: \( a \) is a coefficient of soil linear deformation dependent on its mechanical properties, size of deformor and other factors.

The soil mechanics applies the following formula to determine coefficient of linear deformation of masses of homogeneous soil

\[ \dot{a} = \frac{1-n^2}{E_0} \cdot b \cdot \vartheta \]  

where: \( E_0 \) - a generic deformation module of quasi-homogeneous semi-space;  
\( M \) – coefficient of longitudinal expansion of soil;  
\( b \) – width of loading site;  
\( \vartheta \) – coefficient of the form dependent on \( x = S_t/b \).

In this work it is proposed to determine coefficient \( a \) by the following formula

\[ a = 1.12 \frac{1-n^2}{E_0} \cdot b \cdot x^{0.385} \]  

The process of deformation caused by vehicle running gear is non-linear in the severe soil-earth conditions typical for most cutting areas. To determine general soil deformation, we shall use the following dependence \'\'

\[ h = \frac{a q}{1+b q} \]  

hereinafter \( q \) is a maximum value of running gear pressure; \( b' \) is a value dependent on type of deformation.

In lack of shearing deformations when a rut is formed as a result of soil packing

\[ b' = \frac{a}{h_{max}} \]  

where: \( h_{max} \) is a maximum deformation of soil packing before the state of most dense packing of solid particles at \( q \to \infty \).

In case deformation of water-saturated soils, where shearing deformations prevail, the last extend infinitely at pressure \( q_s \), representing a limit of bearing capacity. In this case value \( b' = -1/q_s \).

Considering that loading of weak forest soils is always accompanied by appearance of packing and shearing deformations, we introduce a formula to calculate generic soil deformation at its one-time loading

\[ h = \frac{a q}{1+h_{max}} + \frac{a q^2}{d_{s-q}} \]
The maximum packing deformation is determined basing on the method of soil equivalent layer proposed by Professor N.A. Tsytovich by the following formula.

\[ h_{\text{max}} = H_0 \left( 1 - \frac{P_0}{(1-W)P_{\text{me}}} \right) \]  \hfill (8)

where: \( H_0 \) – thickness of soil equivalent layer; \( P_0 \) – initial density; \( P_{\text{me}} \) – soil density in the state of most dense packing of particles; \( W \)– soil moisture.

3. The study of accumulation of deformation of soil packing

The complexity of mathematical description of the process of soil deformation at multiple application of load is that as a result of each soil loading its strength properties change and with further vehicle’s trips along its tracks they rest on completely different solid mass where the contraction stresses vary and the packing and sharing deformations develop in a different way.

Relatively low elasticity of forest soils makes it possible to consider them as elastic materials where factors of mechanical properties vary with loading application and remain constant after unloading.

Within the frameworks of the indicated assumption there is a possibility to describe accumulation of deformation of soil packing at multiple trips of vehicles along skidding trails by the following expression

\[ \sum h_{\text{up}} = a_0 q^n \]  \hfill (9)

where: \( n \) - number of trips; \( a_0 \) coefficient of linear deformation of soil at the beginning of first loading.

Analysis of formula (9) demonstrates that the generic soil packing deformation after \( n \)-loading is equivalent to it deformation at one-time application of loading creating pressure \( q \cdot n \).

The nature of accumulation of packing deformations is illustrated by the diagram in Fig. 1 which explains the essence of approach to problem solving.

The shearing deformation at similar degrees of loading follows the geometrical progression law

\[ \sum \Delta h_{\text{c}} = a_0 q^2 \frac{1-\xi^n}{1-\xi} \]  \hfill (10)

where: \( \xi \) – progression denominator

\[ \xi = \frac{2 a_0 q - q^2}{(a_0 - q)^2} \]  \hfill (11)

Figure 1. Accumulation of packing deformations
The generic soil deformation after \( n \)-trip of a vehicle can be found as a sum of packing and shearing deformations. Then the following expression shall be written down to determine the rut depth

\[
\sum \Delta h = \frac{a q q^m}{1 - \frac{n q q^m}{n_{\text{max}}}} + \frac{a q q^2}{q_{v} - q} \cdot \frac{1 - q^m}{q_{v} - q} \frac{\xi}{\xi}
\]  

(12)

Analysis of equation (12) demonstrates that the nature of rut depth growing at multiple trips of a vehicle along the skidding trail depends on the progression ratio value \( \xi \). At \( \xi < 1 \) the rate of rut depth growing reduces with increase of a number of trips and vice versa, at \( \xi > 1 \) the rut depth progressively grows.

Since the progression ratio depends on the running gear pressure \( q \) and limit of soil bearing capacity, let us review the case when

\[
\xi = \frac{2 q_{v} q q^2}{(q_{v} q)^2} = 1
\]

(13)

where we find that the rut depth growth rate rises at \( q_{v} = 0.293 q_{s} \).

Relationship \( q_{v}/q_{s} = K_{v} \), which characterizes the rate of deformation accumulation, is proposed to be called a criteria of rutting intensity [10, 11].

The average pressure of active-bearing sections of timber harvester tracks is determined by empirical formula

\[
q_{cp} = \frac{G}{2 b \left( n_{k} + L \cdot n_{k} \right) n_{k} \sqrt{2 q_{v} q / q_{s}}}
\]

(14)

where: \( G \) – full weight of a skidder with a bundle on a butt plate;
\( n_{k} \) – number of support rollers;
\( L \) – wheel base;
\( q_{cp} \) – average pressure of bearing beam \( q_{cp} = G_{k} / b \cdot L \).

The analysis made in this work demonstrates existing relations between running gear maximum pressure \( q \) and average pressure of active-bearing sections of tracks \( q_{cp} \), as well as dependence of those relations on the type of soil deformation.

Simultaneous consideration of the impact of a large number of factors which significantly vary along the vehicle path makes us correlate the calculation results with experience with regard to final readings of the rut depth.

4. Conclusion

The analysis made in this work demonstrates existing relations between running gear maximum pressure \( q \) and average pressure of active-bearing sections of tracks \( q_{cp} \), as well as dependence of those relations on the type of soil deformation.

The rutting process and soil packing degree are significantly dependent on the vehicle’s vertical dynamics. Researches demonstrate that the vehicle’s speed and design parameters of the running gear affect the values of normal and shear stress formed in the soil.

Implementation of the proposed model shall provide for more reasonable approach to the problem of cutting area development during snowless season, choose rational vehicle systems and technology of their employment.

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References

[1] Melekhov I.S. 1980. Forest science. Forest industry. Moscow. Pages 406.
[2] Pobedinsky A., Zheldak V. 1989. Features of thinning in forests with limited forest
management. *Forestry. Vol. 9. 24-27.*

[3] Kotikov V.M. 1995. Impact harvesting machines on forest soils. *Dissertation of the doctor of technical sciences. Moscow state forest university. Pages 214.*

[4] Klubnichkin E., Klubnichkin V., Krylov V., Kondratyuk D. 2012 To justify the specific pressure of a tracked forestry tractor. *Forestry Bulletin. Vol. 8. 48-50.*

[5] Pirnazarov A., Sellgren U. 2015. Reduced testing and modelling of the bearing capacity of rooted soil for wheeled forestry machines. *Journal of Terramechanics. Vol. 60, 23-31.*

[6] Bottinelli N., Hallaire V., Goutal N., Bonnaud P., Ranger J. 2014. Impact of heavy traffic on soil macroporosity of two silty forest soils: Initial effect and short-term recovery. *Geoderma. Vol. 217–218, 10-17.*

[7] Cambi M., Certini G., Neri F., Marchi E. 2015. The impact of heavy traffic on forest soils. *Forest Ecology and Management. Vol. 338, 124-138.*

[8] Horn R., Vossbrink J., Peth S., Becker S. 2007. Impact of modern forest vehicles on soil physical properties. *Forest Ecology and Management. Vol. 248, Issues 1–2, 56-63.*

[9] Klubnichkin E., Klubnichkin V. 2017 Theoretical foundations of preliminary assessment of the impact of the timber harvesting vehicles on forest soils in the course of logging. *Proceedings of the 19th International & 14th European-African Regional Conference of the ISTVS*

[10] Klubnichkin V., Klubnichkin E., Kotiev G. 2017 Developing a method of theoretical evaluation of the tracked timber harvesting machine undercarriage element loading. *Proceedings of the 19th International & 14th European-African Regional Conference of the ISTVS*

[11] Klubnichkin E., Klubnichkin V., Nakaznova O., Naumov V., Kotiev G., Belyakov V., Zezyulin D., 2016. Influence of the distribution of normal pressures of caterpillar forestry machines LZ-4 and LZ-5 for track formation. *Logging journal. Vol. 6. Issue 3, 167-176.*