Physical and mechanical properties of forest soils: a review

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Abstract: The purpose of our article is to analyze literary sources and supplement classification of soils with missing information that simplifies implementation of mathematical models of the interaction of movers of forest machines with soils. Our research methods include analysis, compilation and systematization of reference and experimental data, and approximation of calculated data. The classification of forest soils by strength categories has been clarified, based on the identification of the characteristic combinations of the physical and mechanical properties of soils — the general deformation modulus, specific adhesion, internal friction angle, specific gravity, and the thickness of the deformed layer. As a result of the analysis of literary sources and calculations, the classification of forest soils has been supplemented with missing information that simplifies the implementation of mathematical models of the interaction of the movers of forest machines with soils. An updated version of the classification includes data on the rheological properties of the soil, the shear modulus, bearing capacity, and the cone index of the soil. Based on the information obtained, linear relationships have been developed that reveal the interconnections of the physical and mechanical properties of soils.

1. Introduction
Modeling the interaction of forest machines with supporting surfaces such as forest soils is an important area of research in the field of forest industry science [1-5]. Based on the results of mathematical modeling, recommendations have been formulated to increase the environmental friendliness of forest harvesting and transport, reduce damage to the forest ecosystems caused by rutting and soil compaction, and the technological efficiency of skidding associated with the ability of vehicles to move across the terrain [1-5]. In forest engineering, mathematical models based on the Russian theory of the movement of road vehicles in off-road conditions developed by Prof. Y S Ageykin [1-5] have attracted considerable attention. The models use several characteristics of the soil, namely, the elastic modulus \( E_0 \), Poisson coefficient \( \nu \), general deformation modulus \( E \), long-term deformation modulus \( E_\infty \), soil viscosity \( \eta \), specific adhesion \( C \), angle of internal friction of the particles \( \phi \), shear modulus \( G \), thickness of the deformed soil layer \( H \), resistance of soil to sensing \( CI \) (cone index), and load bearing capacity \( p_s \) [1-5]. A classification of forest soils by strength categories [6] was previously proposed, based on the identification of the characteristic combinations of the physical and mechanical properties of soils: \( E, C, \phi, \gamma, H \). Unfortunately, not all the characteristics of soils were included in the classical version of the classification.

The purpose of our article is to analyze literary sources, carry out calculations, and supplement the classification of soils with missing information that simplifies the implementation of mathematical models of the interaction of the movers of forest machines with soils.
Research methods consist of analysis, compilation and systematization of reference and experimental data, and approximation of calculated data.

2. Results and Discussion
The long-term deformation modulus $E_\sigma$ and viscosity $\eta$ are introduced when rheological models of soils are used to describe the development of deformations, taking into account the time of impact of the mover. This approach allows us to take into account the influence of the speed of the machine on the rutting and compaction of the soil [7]. The construction of complex combinations of rheological models of soil and their use were considered in [8]; it was shown [7] that the physical phenomena accompanying the formation of a rut can be well described using rheological models of bodies of Maxwell – Thompson and Burgers [7].

It was established [7, 8] that the total and long-term deformation moduli $E$ and $E_\sigma$ are approximately equal:

$$E_\sigma \approx E$$  

In addition, it was experimentally established that the viscosity of forest soils $\eta$ is closely related to the total deformation modulus $E$ [7]:

$$\eta = (0.78 \pm 0.06)E^{1.92 \pm 0.02}$$  

To determine the shear modulus of loose soils, such as sand, the following relationship is used [8]:

$$G = \frac{E_0}{2(1+\nu)}$$  

moreover, the elastic modulus of forest soils exceeds the total deformation modulus by approximately five times [8]:

$$E_0 \approx 5E$$  

However, forest soils are compact; in this case, an estimate of the shear modulus $G$ by the formula [8] is more accurate:

$$G = V_S^2 \frac{\gamma}{g} \approx 290\gamma$$  

where, $V_S$ is the shear strain propagation velocity in the medium ($\approx 53.34$ m/s), $g$ is the gravity acceleration.

To calculate the soil resistance to sensing, the following equation is given in [6, 9-12]:

$$C_I = -C \cot \varphi + \Theta \cdot \frac{24G^m(\tan \alpha + \tan \varphi)(1 + \sin \varphi)\tan \alpha}{d^2 \gamma^2 (m-2)(m-3)(3-\sin \varphi)\tan^2 \varphi} \cdot \left[ C + (Z+\gamma \tan \varphi)^{3-m} - (C + Z \cdot \gamma \tan \varphi)^{2-m} \cdot (C + (Z + 3l - l_m) \cdot \gamma \tan \varphi) \right]$$

where, $d$ is the diameter of the base of a cone pressed into the soil (0.0363 m), $\alpha$ is the angle at the apex of the cone (30°), $L$ is the length of the conical part of an indenter (0.0376 m), $Z$ is the distance from the surface of the soil to the conical part of the indenter (10$L$).

To calculate the bearing capacity of the soil the following equation have been obtained [13-16]:
where, $p_{s0}$ is the bearing capacity with unlimited thickness of the soil layer, $\alpha_z$ is the correction coefficient for taking into account the thickness of the deformed soil layer, $N$ are the coefficients for taking into account the frictional properties of the soil, $\Phi, \Pi, \Phi'$ are supplementary designations, $K$ are the coefficients for taking into account the geometry of the contact area of the mover with the soil, $b$ is the width of the area of contact of the mover with the soil, and $l$ is the length of the area of contact of the mover with the soil.

The characteristic values of the physical and mechanical properties of forest soils [6], supplemented by the results of calculations using formulas (1), (2), (4) – (7), are presented in Table 1.

When calculating the bearing capacity, it is accepted: $b = 0.7 \text{ m}$, $l = 0.8 \text{ m}$, $h = 0.2 \text{ m}$ for soil categories II and III, and $h = 0.05 \text{ m}$ for category I.

### Table 1. Physical and mechanical properties of forest soils of various strength categories.

| Parameter                  | Abbreviation | Unit       | III (weak) | II (medium strength) | I (strong) |
|----------------------------|--------------|------------|------------|----------------------|------------|
| General deformation modulus| $E$          | MPa        | 0.4        | 1                    | 3          |
| Long-term deformation modulus| $E_0$      | MPa        | 0.4        | 1                    | 3          |
| Elasticity modulus         | $E_0$       | MPa        | 2.0        | 5.0                  | 15.0       |
| Shear modulus              | $G$         | MPa        | 2.192      | 2.44                 | 2.77       |
| Poisson coefficient        | $\nu$       | -          | 0.35       | 0.25                 | 0.15       |
| Viscosity                  | $\eta$      | MPa s      | 1.343      | 7.8                  | 64.29      |
| Specific cohesion          | $C$         | MPa        | 0.005      | 0.012                | 0.024      |
| Internal friction angle    | $\phi$      | °          | 11         | 15                   | 16         |
| Specific gravity           | $\gamma$    | MN/m$^3$   | 0.0075     | 0.0085               | 0.0095     |
| Cone index                 | $CI$        | MPa        | 0.243      | 0.464                | 1.003      |
| Load bearing capacity      | $p_s$       | MPa        | 0.0504     | 0.117                | 0.287      |
| Deformed layer thickness   | $H$         | m          | 0.8        | 0.4                  | 0.3        |

The data in Table 1 related to the cone index and the bearing capacity of forest soils are illustrated by the graphs in Figure 1.
Figure 1. Relationship between the bearing capacity and cone index of forest soils and the deformation modulus.

Based on the information obtained, linear relationships have been developed that reveal the interconnections of the physical and mechanical properties of soils — the module of general deformation, load bearing capacity, and cone index. Processing the calculation results shows that the cone index $CI$ [MPa] and the bearing capacity of forest soils $p_s$ [MPa] can be expressed with high accuracy by the linear functions of the general deformation modulus $E$ [MPa]:

$$CI = 0.2866E + 0.1497$$

$$p_s = 0.0895E + 0.0202$$

3. Conclusion

Earlier, a classification of forest soils by strength categories was proposed, based on the identification of the characteristic combinations of the physical and mechanical properties of soils — the general deformation modulus, specific adhesion, internal friction angle, specific gravity, and the thickness of the deformed layer. As a result of the analysis of literary sources and calculations, the classification of forest soils has been supplemented with missing information that simplifies the implementation of mathematical models of the interaction of the movers of forest machines with soils. An updated version of the classification includes data on the rheological properties of soils, the shear modulus, load bearing capacity, and the cone index of the soil. Based on the information obtained, linear relationships have been developed that reveal the interconnections of the physical and mechanical properties of soils — the module of general deformation, bearing capacity, and cone index.

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