Experimental determination of soil shear force by track model depending on track surface to soil friction coefficient

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Abstract. Results of experimental research of track surface to soil interaction at different track-to-soil friction coefficient are given. Maximum force at track was determined. The obtained values were compared with estimate results. It has been found that the track traction properties are slightly changed upon varying track-to-soil friction coefficient, with the friction coefficient reducing, the track traction properties improve. When calculating, it is necessary to use the static friction coefficient which considers insufficient movement of the limit equilibrium area along the track.

1. Introduction
The tractor's traction-friction properties are much dependent on the track parameters. The track traction properties can be changed by changing its geometrical dimensions: length, width, height of grouser, shape, location of grousers, coefficient of track material to soil friction. When reviewing track interaction with soil using loose medium statics methods, it has been demonstrated [1] that the track traction properties can be drastically improved by using materials with low friction coefficient. This assertion made on the basis of the theoretical research needs an experimental validation since controversial conclusions were made concerning track-to-soil friction coefficient impact on the friction properties of the tracked running gear when the track-to-soil interaction was reviewed by different methods [2].

2. Result of experimental research
Track model interacting with soil at different track-to-soil friction coefficients is considered in the paper. The equipment shown in Figure 1 was used allowing to determine maximum traction force on the track model $P$, depending on physical and structural properties of soil, geometrical dimensions of the track and vertical load on the track. The equipment consists of frame 1, cargo bed 2, blocks 3, brake 4, cable with chain 5, track model with loads 6, a measuring platform with dial gauge 7. The brake is used to fix cable 5 when placing loads on the cargo bed 2. Experimental data obtained when studying physical models of the track were compared to the calculated values. A 2-D model [3] built on the loose medium statics methods [4] were used as a mathematical model of interaction between the track and soil. In this model the maximum permissible shear stresses on the bearing pad are defined by Coulomb's law and the soil mass is not taken into account.
The work was carried out in section 26B of Khotkovo district forestry of Sergiev-Posad branch of SPI Mosoblles. Physical and structural properties of soil were determined in one place [5, 6]. The obtained results are given in Table 1.

Table 1. Soil physical and structural properties

| Characteristic                          | Value          |
|----------------------------------------|----------------|
| Soil type                              | Sod-podzol, loam |
| Plasticity number                      | 12             |
| Soil particle density, g/cm³           | 2.33           |
| Soil humidity in layer 0 – 5 cm, %     | 36.81          |
| Soil density, g/cm³                    | 1.54           |
| Dry soil density, g/cm³                | 1.12           |
| Soil relative humidity, %              | 80.24          |
| Internal friction angle ρ, deg/rad     | 21.8/0.4       |
| Soil adhesion C, H/cm²                 | 1.0            |
| Track-to-soil friction angle ω, deg/rad|                |
| - sand paper P40                       | 36.8/0.642     |
| - steel                                | 26.4/0.461     |
| - steel with silicone grease           | 23.9/0.417     |

Soil humidity was determined by drying the soil to the fixed mass, soil density was determined by the cutting ring, dry soil density was determined by calculation method, soil particle density was determined by pycnometer method with water, liquid limit was determined by cone penetration, plastic limit humidity was determined by rolling into rope, internal friction angle and soil specific cohesion were determined by single-plane cut method.

Track-to-soil friction coefficient $\tan \omega$ was determined by dragging a plate made of track material over soil [8]. When carrying out the work, plates covered with sand paper P40, steel surface treated with sand paper P800 and covered with silicone grease were examined. Treating plates with abrasive material of M20 grade [7] (sand paper P800) simulates surface of a track running over loam soil. The plate was loaded with load of mass $m=47$ kg and then force $m_1g$ necessary to commence plate movement was determined (Figure 1). Load mass $m_1$ was increased stepwise. At each step the plate...
movement was recorded by the dial gauge ICh 10 0.01. The experiment was terminated when at the next stepwise increase of load mass $m_1$, the plate started moving constantly. Fig. 2 shows the relations obtained between plate movement and load mass $m_1$. It is necessary to note that as the loading pattern was changed, the type of relations given in Figure 2 may change.

Figure 2. Relation between plate movement and load mass $m_1$

1 – steel surface treated with sand paper P800 and covered with silicone grease;
2 – steel surface treated with sand paper P800;
3 – surface covered with sand paper P40;

Track physical models were examined at the place where soil properties were determined. Track model dimensions are the following: width $b=30$ cm; grouser height $h=4$ cm; contacting area length $l=21$ cm. Examined were tracks with running surface covered with sand paper P40, steel running surface treated with sand paper P800 and steel running surface treated with sand paper P800 and covered with silicone grease (Figure 3).

Figure 3. Track models: a) track with running surface covered with sand paper P40; b) track with steel running surface treated with sand paper P800

To interpret the results obtained at physical modeling, it is necessary to consider mechanical similarity. During physical modeling of limit equilibrium of loose medium the law of mechanical
similarity consists in that in geometrically similar domains with equal numbers $\rho$ and $\gamma l/p$ the reduced stresses in respective points are similar if they are similar at the boundaries [4], where $\rho$ is a soil internal friction angle, $\gamma$ is a soil bulk density, $l$ is a reference length, $p$ is a reduced stress. Since during interaction of the tractor’s track with soil, the weight of the interacted soil is low as compared to the tractor’s weight and created tractive efforts, the soil weight can be ignored. Thus in our case the mechanical similarity condition will be geometrical similarity of the tracks, similarity of the reduced boundary stresses and equality of internal friction angle of the model and full-scale specimen.

The physical models were examined as follows: the soil is leveled off; cuts according to the track grouser size are made in it; track is earthed. The total mass of the track and load is $m = 47$ kg. Lateral force is applied to the track and increased until the track is broken down (Figure 1). The results obtained are given in Table 2.

**Table 2. Maximum lateral force determination results**

| Track surface       | Maximum horizontal force $P_y$, H | Accepted values of coefficient / track-to-soil friction angle |
|---------------------|-----------------------------------|-------------------------------------------------------------|
| Sand paper          | 1,410                             | 345/198                                                     |
| Steel               | 1,480                             | 0.341 / 19.6                                               |
| Steel with grease   | 1,525                             | 0.338 / 19.3                                               |

3. **Analysis of experimental results**

To use mathematical model [3] it is necessary to know track-to-soil friction angle $\omega$. In this case condition $\omega \leq \rho$ should be met. As follows from Table 1 this condition fails to hold. In mathematical model [3] friction angle $\omega$ is used to review interaction between soil limit equilibrium area and track surface. This area moves together with the track and track’s displacement relative to the limit equilibrium area is insufficient. Figure 2 shows that with track’s little displacement relative to the soil, the friction angle (friction angle at rest(static)) varies from zero to the internal friction angle value given in Table 1. Let us take values of a track-to-soil friction angle $\omega$ at which estimated values of maximum lateral force $P_y$ are equal to experimental. The calculation algorithm is given below.

By substituting values of soil structural properties from Table 1 and values of a track-to-soil friction angle from Table 2 into mathematical model [3] we obtain estimated values of maximum lateral force $P_y, H$:

$$P_y = b \left( h \sigma_{ky} + l \sigma_{kx} \tan \omega \right),$$

where $\sigma_{ky}$ is ground pressure standard for a grouser, H/cm$^2$,

$$\sigma_{ky} = \sigma_y \left( 1 + \sin \rho \right) \frac{\sin(\varphi_y - \delta)}{\sin(\varphi_y + \delta)} - C \tan \rho;$$

$\sigma_y$ is an average reduced standard pressure arising under action of this grouser, H/cm$^2$,

$$\sigma_y = \frac{\sigma_{kx} + C \tan \rho}{1 + \sin \rho \cos(2\varphi_y)};$$

$\sigma_{kx}$ is ground pressure standard for a track plate, H/cm$^2$,

$$\sigma_{kx} = \frac{mg}{bL};$$

$\varphi_y$ is an angle between grouser and direction of main stress component $\sigma_{max}$ acting from the track plate,

$$\varphi_y = \frac{\pi}{2} - \frac{1}{2} \left( \arcsin \frac{\sin \omega}{\sin \rho} - \omega \right).$$
is an angle between line of discontinuity and reduced stress close to the line of discontinuity,
\[ \delta = \arcsin\left(\sin \varphi_y \sin \rho\right) \]

\( L \) is a length of limit equilibrium area, cm

\[ L = h \frac{1 + \cotg(\alpha) \cotg\left(\varepsilon - \left(\frac{\pi}{2} - \varphi_y\right)\right)}{\cotg(\alpha) + \cotg\left(\frac{\pi}{2} - \varepsilon\right)} , \]

\( \alpha \) is tilting angle between line of discontinuity and a grouser,

\[ \alpha = \frac{1}{2} \left( \arcsin\left(\frac{\sin \delta}{\sin \rho}\right) + \delta \right) ; \]

\( \varepsilon \) are tilting angles between sliding line and direction of sliding\n
\[ \varepsilon = \frac{\pi}{4} - \frac{\rho}{2} . \]

4. Conclusion
1. Experimental research has shown that tracks with variable coefficients of running surface to soil friction have close friction properties. However, tracks with lower friction coefficient have better friction properties.
2. When mathematical model [3] is used, a track surface to soil friction angle should be taken as friction angle at rest (static) within the range from zero to the value of internal friction angle.

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