The study on soils external friction

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Abstract. The molecular-mechanical (adhesion-deformation) theory of friction with respect to a dispersed medium was confirmed in the article on the basis of theoretical and experimental soils external friction studies. At the same time, the soil particles interaction calculated model of a spherical shape with a smooth polymer surface was developed and an expression for determining the area of their actual contact with a solid surface under the action of a load N was obtained. The calculated contact area results' comparison for coarse and fine sand showed satisfactory convergence with the experimental data (discrepancy does not exceed 8-10%). The particles behavior analysis of the dispersed medium adjacent to a solid smooth surface under shear, presented in the computational model, was confirmed by the experimentally obtained and fixed plastic deformations of the polymer surface layer. The experimental studies using a soil tribomer allowed to determine the deformation proportion and adhesive components in the external friction force of sandy and clay soils. Using the obtained dependencies for calculating and contacting soil particles with a solid surface, a method for calculating the coefficient of external friction of the soil based on the molecular-mechanical theory of friction is proposed.

Introduction

In industrial and civil construction, during the buildings and structures erection the friction of soils on hard surfaces (external friction of soils) is constantly met. The friction of soils in pile engineering construction, in the lowering structures construction, in the development of soils by building machines, in puncturing embankments, etc. is especially important. However, to date, little attention has been paid to the issues of studying the soils external friction.

The soils friction force in construction is determined, as a rule, on the basis of statistical data, by the specific friction forces, without deep scientific analysis of the soils interaction with solid surfaces.

The friction science development history is presented in [1]. At the same time, recent advances in the study of soil friction [2,3,4], in the field of the friction theory and the solids wear [5,6,7], in the theory of a granular soil environment [8] allow to develop the soils external friction idea from the friction modern molecular-mechanical theory perspective.

In view of the above-mentioned, the purpose of this paper is:

- to confirm the main provisions validity of the molecular-mechanical (adhesion-deformation) theory of friction with respect to the soils external friction.

Based on the goal, the following tasks were solved:

- to study the nature of the discrete medium contacting (soil) with a solid smooth surface by developing a design model;
- to establish the smooth solid (polymer) surface deformation nature and the behavior of soil particles under the action of normal and tangential forces;
- to identify the changes dynamics in the deformation and adhesive component of the soil external friction force;
- to develop a method for determining the friction coefficient of external soils friction.

Based on the purpose and objectives of the study, a computational model of interaction (contacting) of a granular medium with a smooth solid surface was developed, taking into account their convergence under the action of normal pressure $N$. The proposed model is shown in Figure 1.

**Figure 1.** A granular medium with a smooth surface interaction computational model, taking into account their convergence under the action of normal pressure $N$, as well as baseline data for calculating the actual contact area and friction force under tangential displacement under the action of shear pressure $T$.

**Main part**

When studying the contact area of a granular medium with a smooth solid surface (see Fig. 1), the soil model was represented from the particles of a rounded homogeneous discrete system. Moreover, their convergence under load $N$, the introduction of particles into a hard surface was modeled as spherical elements with radius $r$ and the nearest contacts, according to the principle of Saint-Venant, do not affect each other, i.e. It is assumed that there is a unique connection between the load and the deformation on the contact patch.

The surface of the solid body $AA$ is taken as the base for reading the value of the approach of the soil particles to the solid surface. All soil particles whose vertices lie below line $AA$ will come into contact, and the general convergence of soil particles will be achieved under the condition that each $i$-th particle, among those that have come into contact, moves closer to the solid surface by the value of $h_i$. The numerical approximation is equal to the maximum penetration of soil particles into a solid - $h_{\text{max}}$.

At a distance $x$ from the maximum penetration top of a particle into a solid, we select a layer of thickness $dx$. All particles which vertices are located in this layer will be implanted in a solid by an equal amount equal to $\varepsilon$-$x$, where $\varepsilon$ is the relative incorporation of soil particles into a solid, equal to:

$$\varepsilon = \frac{h_{\text{max}}}{R_{\text{max}}}; \quad x = \frac{X}{R_{\text{max}}};$$

$$G_H = \frac{N}{S_H}$$
$x$ is the dimensionless coordinate (variable value of $\varepsilon$);

$R_{\text{max}}$ - the soil particles penetration greatest depth into a solid (for the studied normal pressures of $0.1\text{–}0.3$ MPa, $R_{\text{max}} = 0.05\text{–}0.12$).

Taking the function $\varphi(x)$ - continuous, we calculate the number of particles, the vertex of which is in the layer between the levels $x$ and $x + dx$.

$$dn_i = n_i \varphi(x) dx; \quad (2)$$

Taking the Saint-Venant principle into consideration, there is a one-to-one relationship $N = N(\varepsilon - x)$; we find the load on all the implanted particles in a solid, which vertex coordinates are located in the $dx$ layer:

$$dN = n_i N(\varepsilon - x) \varphi'(x) dx; \quad (3)$$

After summing over all the layers where the soil particles are embedded in the radius $r$ spheres form, the equation relating to the soil particles penetration amount to a solid surface with an applied load is obtained:

$$N = n_i \int_0^\varepsilon N(\varepsilon - x) \varphi'(x) dx; \quad (4)$$

The function $N = N(\varepsilon - x)$ is expressed by the average normal pressure on the contact $P_r (\varepsilon - x)$ and the single contact area projection on a flat parallel to the smooth surface is:

$$S^0_i = \alpha S^0_r, \quad (5)$$

where $S^0_i$ is the cross-sectional area of a soil particle that has penetrated into a solid by $\varepsilon - x$ from its tip (see Fig. 1).

The coefficient depends on the contact type (elastic or plastic). In our case, when contacting the polymer surface, the contact is plastic.

For a spherical model, from geometric considerations, the area $S^0_i$ for a single fixed contact can be calculated by the formula:

$$S^0_i \approx 2\pi r R_{\text{max}} (\varepsilon - x), \quad (6)$$

Giving a normal pressure of $N = 0.025\text{–}0.4$ MPa, the spherical particles radius $ds.b. = 2r$ (for gravelly sand $2r = 2.3 mm$, for coarse sand $2r = 1.155 mm$, for fine sand $2r = 0.172 mm$), the number of particles which vertices are in the layer between $x$ and $x + dx$ was calculated.

In our case, the transition condition from elastic to plastic contact, according to [9], is determined by the coefficient $\alpha = 2.76 \tau_y$. For coarse and fine sand, the actual contact area with a smooth polymer surface was calculated using the formula (2).

The theoretical results obtained for these sands were subjected to experimental verification. For this, we have studied the above-mentioned sandy soils contact area formation with a solid smooth polymer surface, using the particles impressions on it at a normal pressure of $0.025\text{–}0.4$ MPa. Each experiment was repeated up to 10 times, the experiments results variation was 7-10%. Figure 2 shows the theoretical calculations comparison results and the actual contact area experimental determination.
Figure 2. The theoretical and experimental results comparison of determining the relative actual contact area of soil particles with a solid smooth surface for sand: 1 - gravel; 2 - large; 3 - small; 4 - the experimental data results (taking the variation into account).

A soil particles interaction process study with a solid polymer surface with their tangential displacement was carried out on the installation we had developed — a soil tribometer (made on the basis design of the Hydropoint shear device) and presented in [10].

On the computational model of contacting loose soil particles with a solid surface (see Fig. 1), seven basic soil particle locations that come into contact with a solid smooth surface under normal pressure \( N \) are presented. The particles 1, 2, 3 and 4 came into contact and infiltrated into a solid by the value of \( h \).

As tangential pressure \( \tau \) increases, the above-mentioned particles 1-4 are affected by the shearing forces \( t \) and confining \( n \). Particle 5 is affected only by the shearing force (without holding force); only normal force acts on particle 6 (no tangential force); particle 7 is not subjected to force. From the presented model, the soil friction force is formed at the particles contact points 1–4, i.e. \( T = T_1 + T_2 + T_3 + T_4 \).

To confirm our proposed model compliance of soil interaction with a solid surface on a soil tribometer, we obtained the smooth polymer surface deformation character when sand is coarse over it by 5.0 mm under 0.1 MPa pressure. The result obtained is shown in Figure 3. The deformation nature analysis of a solid surface with a tangential soil displacement - confirms the presence in the layer of particles adjacent to a solid surface of a granular medium that are in different positions relative to the solid surface and exert different effects on it during friction.

Figure 3. The deformation nature of a smooth polymer surface when shear coarse sand by 5.0 mm under 0.1 MPa pressure (x 50)
The change dynamics in the deformation and sandy soils external friction force adhesion components was investigated on a soil tribometer [10] using the method of AD. Kuritsinoy [11]. According to this method, the friction force adhesion component is determined by the total external friction force reduction using a thin layer of lubricant (100-120 mm thick) deposited on a solid surface. Silicone grease was used in our experiments.

Since the lubricant layer eliminates the adhesive interaction between the rubbing pair, the adhesive component was determined by the difference between the total friction force $T$, which corresponds to the coefficient $f$ and the adhesive component of the friction force $T_g$, which corresponds to the coefficient $f_g$.

Fig. 4a presents the coarse and fine sand external friction separation results into deformation and adhesive components when their humidity changes. On fig.4.b, the separation of external friction of clay is presented when its humidity changes.

The obtained results analysis showed that the sandy soil external friction force is formed mainly due to the deformation component $f_g$, the adhesive component during the sandy soil friction does not exceed 5-10%.

The air-dry humidity clay soil external friction is mainly formed by the deformation component (curve $f_g$, Figure 4b). With an increase in the moisture content of the clay to the rolling limit, the absolute value of the friction force increases, and the proportion of the adhesion component increases from 8 to 65-70% (curve $f - f_g$, Fig.4b).

Further clay moistening causes an intense decrease in the friction force absolute value, while the adhesion component proportion continues to increase. When the clay moisture content is close to the yield point, the external friction force decreases 3.5 times, and the adhesive component proportion increases to 85%.

Based on the friction molecular-mechanical theory [5], taking into account the expressions (4) and (6) contributing to the computational model of contacting a granular medium with a smooth solid surface, the external friction coefficient of bulk soils can be calculated using the equation:

$$f = \frac{h \cdot \sigma_f}{S_\sigma \cdot \sigma_N} + \frac{\sigma_{\tau_0} \cdot S_\tau}{N}.$$  

(7)
where \( h \) is the deformed zone depth (see Fig. 1);
\( S_0^w \) - is the average diameter of a single friction coupling, determined from the expression (6);
\( \sigma_n \) - is the average stress of pushing the material of a solid surface in a tangential direction, defined as a quotient \( \frac{T}{S_0^w \cdot n} \);
\( \sigma_N \) - is the average voltage on the area of the actual contact, defined as private
\( S_{aw} \) - is the films actual contact area
\( N \) - defines vertical pressure.

Summary
Thus, based on the study results, the following conclusions were made. The nature study of contacting a discrete medium with a solid surface made it possible to establish that the soils external friction force is formed at the actual contact points. At tangential displacement of these particles, an elastic, elastoplastic displacement of the solid surface material a occurs. The soil particles adjacent to a solid surface experience very different stress - strain states; particles subjected to only a normative load, particles experiencing only tangential force, particles under the influence of normative and tangential loads create a force of external friction and particles not experiencing any loads.

Tribometric studies conducted with sandy clay soil allowed to establish that the external friction of soils, as well as the solid friction, complies with the friction molecular-mechanical theory. In this case, the sandy soil friction force is formed mainly due to the deformation component, and the friction force of the clay soil, depending on its humidity, has a complex relationship. But within the natural humidity limits, the clayey soil friction force is 70-85% formed by adhesive bonds.

In the further soils external friction study, we believe it is necessary to establish the effect on the friction force of soils on the solid surface roughness and physical and mechanical properties. The clay soils external friction and their contact with solid surfaces are not considered in detail. The issues of regulating (increasing or reducing) the external friction of soils require their solution.

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