New Approach to Assessment of Granular Soil Shear Strength in Road Pavement

A V Moshenzhal¹, S M Zhdanova², A A Piotrovich²

¹Technical Director LLC «Miakom SPb» Bldg. 47, Wing 2, Stachek Ave., St. Petersburg, 198097, Russia
²Construction Chair, Far Eastern State Transport University, 47, Serysheva str., Khabarovsk, 680021, Russia

E-mail: piotrovich@rambler.ru

Abstract. The article provides a new approach to assessment of granular soil shear strength in road pavements made of paving stones from the point of view of granular medium mechanics. The new approach consists in considering the features of normal and shear stress distribution in the multilayer structure of road surfaces made of artificial paving stones. The results of new approach make it possible to judge upon reasonability of considering the discrete structure of granular materials used in transport construction.

1. Introduction
The road pavements made of paving stones are equally efficient both for service reliability of the surface structures for the increased loads and for pedestrians, as well as for light vehicles during the territory improvement. These surfaces proved to be suitable as the material ensuring high process and operational characteristics as compared to the other pavements [1].

The road pavements made of paving stones in the Russian Federation are estimated as per the requirements of the regulatory documents [2, 3, 4] for the allowed elastic defect and shear strength. The significant simplifications in this regulatory documentation represent the use of elasticity theory solutions according to which the layers of the granular material arranged under the paving stones are considered to be solid isotropic material, as well as impossibility for taking into account the features of the loose layer structure of the base. Forecasting the behavior of such surface under the load does not consider the pressure propagation from several paving stones and the stress distribution mechanism in the road-mat mass, including when deciding on the structures with geosynthetic materials. Sometimes this may lead to the economically and technically unjustified design solutions when deciding on the materials and selecting the thickness of the road structural layers.

The efficient criterion for assessment of the selected types of grounds and thicknesses of the road structural layers is the check of meeting the shear strength condition in these layers. It is obvious that to check the shear strength, the features of normal and shear stress distribution propagated from layer to layer in the depth should be determined. The latter depends on the characteristics of grounds of structural layers and features of pressure propagation to the pavement. This is mostly relevant for assembly structures, for example, made of artificial paving stones proven to be successful technological and reliable solution.
Today, the prospective field in studying the stress distribution in the granular soil of road structures made of artificial paving stones is the granular medium mechanics [5]. The pressure propagation mechanism of the artificial paving stone surfaces to the granular soil, as well as consideration of the characteristic normal and shear stress distribution in the calculations is poorly studied. That is why the article covers this relevant problem that consists in developing the comprehensive approach to the forecast and design-theoretical substantiation of the shear strength criterion for the granular soils of the pavements made of artificial paving stones. The comprehensive forecast of processes occurring in the loose grounds under surface load will make it possible to take into account the features of such grounds and structures made of them for practical application in transport construction.

2. Materials and methods
It is known from the studies provided in work [6] that several paving stones participate in the pressure propagation outside, under the surface load. This is due to the stone friction in joints. It is obvious that in each case the friction force and, as a consequence, the quantity of the stones involved will be different for different types of joint fillers. The geometric parameters of the stone blocks, the nature and point of the surface load, as well as the structural features of the underlying layers of the ground are of importance.

The task related to the pressure propagation and distribution through such pavement can be conditionally divided into two parts. The first part consists in determining the values of the pressure propagating from the stamp or wheel to the paving stones, and the second part consists in determining the nature of the pressure distribution from the stones to the underlying layers of the road structure that is necessary to check meeting the shear strength condition in granular soil. In the other works, for example, [7, 8], we represent the solution in the plane formulation that is obvious to have certain tolerances as it does not take into account the spatial nature of the propagated pressures from the involved paving stones. Further on this topic, this article offers the solution of this task in the plane formulation.

One of input parameters in three-dimensional format is point of load application, i.e. pavestones (included into load transfer to sublayers action) quantity determination. It is important to take into account stones’ geometrical parameters, their sequence on earlier prepared base or structural layers. Let’s consider case of pressure transfer (from evenly distributed load along circle with radius 0, 17 m) to pavestones, which have the following geometrical characteristics: width -0, 10 m, length – 0,20 m, thickness – 0,07 m. (figure 1).

![Figure 1. Determination of being-in-use paving stones quantity scheme.](image)

We are supposed to make some notes for the purpose of task finding solution:
1. The pressure under all applied pavestones isn’t the same and depends on press tool area of bearing to each pavestone;
2. The below presented solution doesn’t consider frictional force between related stones.
3. There are no rotational inputs in stones during pressure transferring (to pavestones).
To reassure the first (above) statement we should introduce a concept of fraction of pressure (to a certain stone from surface loading). This is just probabilistic observation and it is determined as the ratio of surface area loading on block pavement to punch area for each stone. (1).

\[ q_i = \frac{S_i}{S}, \quad (1) \]

It should be noted that valuated amount of \( q_i \) should be equal to «1».

A method of accounting of joint seal between pavestones is an important technical and also economical aspect. Obviously, the tighter coupling between pavestones the more bearing area and the less normal and shear stresses in the ground. As for the second mentioned above statement, dropping of frictional force between related pavestones allows us to get more reliable design decisions.

Artificial stones of pavement are presented by solid pavement blocks, i.e. the pressure doesn’t split up in horizontal direction to related stones due to frictional force absence between them. Thus, each separated stone is presented by little rectangular parallelepiped punch. This article presents decisions for equal load distribution through a square.

There are decisions (2) – (7) for the purpose of values of normal and shear stresses determination in multilayer constructions in granular media mechanic sphere [5].

\[
\sigma_{i}^{\text{max}} = \frac{p}{4} \left( \Phi \left( \frac{x+b}{(h_i+z)\sqrt{2v_i}} \right) \Phi \left( \frac{x-b}{(h_i+z)\sqrt{2v_i}} \right) \Phi \left( \frac{y+a}{(h_i+z)\sqrt{2v_i}} \right) \Phi \left( \frac{y-a}{(h_i+z)\sqrt{2v_i}} \right) \right),
\]

\[ h_i = h_{i-1} \frac{v_i}{v_{i-1}} + h_i \frac{v_{i-1}}{v_i} + \ldots + h_{i-1} \frac{v_{i-1}}{v_i}, \quad (3) \]

\[ \tau_{xz} = -vz \frac{\partial \sigma_z}{\partial x}, \quad (4) \]

\[ \tau_{yz} = -vz \frac{\partial \sigma_z}{\partial y}, \quad (5) \]

\[ \sigma_x = v \sigma_z + v^2 z^2 \frac{\partial^2 \sigma_z}{\partial x^2}, \quad (6) \]

\[ \sigma_y = v \sigma_z + v^2 z^2 \frac{\partial^2 \sigma_z}{\partial y^2}, \quad (7) \]

\( p \) is the intensity of the applied pressure, \( kN/m^2 \) is the coefficient of distribution of the soil layer or base; \( b, a \) - half the width of the load band along the \( X \) axis and \( Y \) axis respectively, \( m; X, Z, Y \) - coordinates of the test point in the \( X0Z \) and \( Y0Z \), \( m; \sigma_z \) - vertical stress, \( kN/m^2; \sigma_x, \sigma_y \) - horizontal stress; \( kN/m^2; \tau_{xz}, \tau_{yz} \) - shear stress, \( kN/m^2; h_i \) - pavement layer thickness, \( m; \Phi \) - error integral; \( v \) – elastic modulus; \( h_e \) - equivalent thickness of layer, \( m \).

These data let taking into account stress from one paving stone, but don’t outline a concept of values \( \sigma_z, \sigma_x \) and \( \tau_{xz} \), distribution type during application of several surface load. This question hasn’t been under consideration in the sphere of granular media mechanics earlier. For this task solution finding, we can use the formula (8).
with, $\xi = \pm a_i; \chi = \pm f_i$,

where $l$ – is a half of a paving stone length, $m$; $c$ – is a half of a paving stone width, $m$; $a_i, f_i$ - central point location of paving stone $i$ relating to zero along axis $X$ and $Y$, correspondingly, $m$; $n$ - paving stones, which are involved in the process of pressure propagation.

As mentioned earlier, to provide high rate of surfaces reliability it is necessary to provide conditions of shear strength in constructive layers or in base, which is made of lowly cohesive layers in the most critical point that can be characterized by highest values of vertical stress. From the space position, the same task is being more complicated as far as it is necessary to take into account stress distribution type from each pavement element.

Using above presented suppositions and hypothesis, as well as design model (figure 1) we are going to determine critical point position in terms of vertical intensity. For this purpose, the following set of simultaneous equations has been made (figure 2). Solutions to equations have been accomplished in software package MathCAD.

\[
\sigma_{2(распев)} = \frac{P}{4} \sum_{i=1}^{n} \left[ \Phi\left( \frac{x + \xi_i + l}{(h_i + z)\sqrt{2v}} \right) \cdot \Phi\left( \frac{x + \xi_i - l}{(h_i + z)\sqrt{2v}} \right) \right] \times \left[ \Phi\left( \frac{y + \chi_i + c}{(h_i + z)\sqrt{2v}} \right) \cdot \Phi\left( \frac{y + \chi_i - c}{(h_i + z)\sqrt{2v}} \right) \right],
\]

(8)

Figure 2. Screenshot of a computer with picture of set of simultaneous equations and initial data for calculations in MathCAD.
The performed calculations do not consider the ground dead weight, and the ground distribution ability factor is taken to be equal to 0.350 based on the previous studies. You can find results of calculated values of vertical stresses at different depth from the bottom of paving stones (below).

Analyzing received types of vertical stress distribution, we can draw the following conclusions:

1. In accordance with calculation model presented in picture 1, the maximal stress emerges from paving stone No. 5; it is in keeping with the results presented in picture 3;

2. Presented system of equations let determine values of stress at any point of solid soil with account for stress distribution inequality over paving stones.

Having picture of vertical stress distribution at soil, we can easily determine missing values (using formulas (4) – (7) of stress and check shear strength conditions in the most critical point of granular soil or constructive layer. It is well known from the classical mechanics of soil that condition of shear strength has to be provided at all the points of soil body and is being expressed by in equation, where value of active shearing stress hasn’t to exceed the value of allowable shearing stress. According to [9] this condition can be presented through the following in equation:

\[
(\sigma_1 - \sigma_2) \sin 2 \left(45 \pm \frac{\theta_{\text{max}}}{2}\right) < \left[\sigma_1 + \sigma_2 + 2 \sum_{i=1}^{n} (h_i \gamma_i) + \frac{2c}{\tan(\phi)} + (\sigma_1 - \sigma_2) \cos 2 \left(45 \pm \frac{\theta_{\text{max}}}{2}\right)\right] \tan(\phi) + 2c, \quad (9)
\]

where, $\sigma_1, \sigma_2$ - values of the main stresses, MPa; $\theta_{\text{max}}$ - the angle determining the value of the deviation of the total stress acting on the site under consideration, from the normal to it, grad; $h_i$ - the thickness of the structural layer, $m$; $\gamma_i$ - unit weight of soil, kN/m$^3$.

It should be noted that the left part of the inequation (9) reflects the value of the active shear stress $\tau_a$, and the right part - the maximum permissible active shear stress $\tau_{\text{max}}$.

Above presented – formulas and prerequisites of granular media mechanics let estimate the pressure propagation irregularity from a wheel or a punch to a paving stone blocks and also complete tasks about type of normal and shear stress distribution and their values in underlying layers of pavement or base structure.

Design recommendations for paving stones of coating [2, 3] include presurmise of possibility not to take into account assembly paving and levelling course in the construction calculations. In this case, as
noted above, structural features of levelling layer of sand, geometrical parameters of paving stones and characteristics of stress distribution are not under consideration here. For comparison of the results, which were obtained according to solutions of legal requirements [2, 3, 4], with accounting results by the offered procedure we are supposed to use initial data, presented in table 1. The accounting is accomplished according the shear-resistance factor in lowly cohesive soil of base, more specifically, in sand clay.

Table 1. Initial data for verification of shear strength conditions.

| № | Load, MPa | Indentation diameter, m | Material | \( E \) (elastic deformation), MPa | \( c \), MPa | \( \phi \), degree | \( \gamma \), kN/m\(^3\) | \( \nu^2 \) | \( h_i \), m | \( A_{as} \times b_{as} \), m |
|---|-----------|------------------------|----------|---------------------------------|------------|----------------|----------------|--------|--------|----------------|
| 1 | 0.5 | 0.34 | Paving stone | 1350 | - | - | - | - | 0.07 | 0.10x0.20 |
| 2 | sand | 50 | 0 | 32 | 17 | 0.1346 | 0.05 | - |
| 3 | crushed stone | 360 | 42 | 19 | 0.1403 | 0.15 | - |
| 4 | sand clay | 15 | 0.005 | 33 | 26 | 0.230 | - | - |

Note: The values of indexes of distributive capability \( \nu \) are taken as an example on the basis of analysis of the studies of A.V. Matveev [10]

As far as surface consists of several layers it is necessary to take into account stress transmission in next layers with allowance for stress distribution in previous layers (for testing conditions of shear-resistance in some point of structure), i.e. it is necessary to cope with a task for multilayer structure. For this purpose, we use formulas (2), (3). Design model is presented in picture 1.

In accordance with presented earlier methods, profile with maximum value of vertical stress in foundation soil. (figure 4).

![Figure 4](image_url)

**Figure 4.** Vertical stress distribution in base soil at the depth of 0.27m from the top of coating.

The results of performed accountings according to working and offered methods are presented in table 2.
Table 2. The results of comparative calculations.

| № | subsoil     | design parameter | measurement unit | Analysis according to [4] | Offered method |
|---|-------------|------------------|------------------|----------------------------|----------------|
| 1 | Sandy loam  | $D_p$            | m                | 1.180                      | -              |
| 2 |             | $\sigma_x$      | MPa              | 0.0415                     | 0.0925         |
| 3 |             | $\sigma_c$      | MPa              | -                          | 0.0212         |
| 4 | Sandy loam  | $\tau_{xz}$     | MPa              | -                          | 0.00000000433  |
| 5 |             | $\tau_{lim}$    | MPa              | 0.00956                    | 0.0989         |
| 6 |             | $\tau_{a}$      | MPa              | 0.0065                     | 0.0719         |
| 7 | shear strength condition | -               | ok               | ok                         | ok             |

We can draw the following conclusions:

• The difference between values of vertical stress, which are obtained according to normative and offered hereby technique of accounting, is by several times. In such a case, underestimating of vertical stress value to foundation is going on;

• According to the calculation results, the shear resistance condition is met in both cases;

• The critical point in the calculation methods [4] is placed along the axis of applied load (stress) $X=0$, $Y=0$, whereas in compared methods $X=0$, $Y=-0.25$. Consequently, a designer has more advantages to choose the adequate measures to provide shear-resistance (using offered calculation procedure), for instance, with the use of geosynthetic materials [11, 12, 13], and also with their justified disposition in a block of soil or with variation of thickness of structural layers;

• When using decisions, presented in [4], stress distributes in an angle 45 degrees from load application surface, but it isn’t crucial hypothesis, because the following factors (that influence stress distribution nature) don’t come into account: compression ratio, intermediate size of elements, modulus of deformation, etc.

3. Conclusion
Forecasting the surface service life needs considering the features of the road structural layers and their functioning under load during operation in order to ensure movement.

The calculations performed to check meeting the shear strength condition of the grounds of the surface base made of artificial stones should consider the features of the pressure propagation from each stone in particular and in general, as this influences the determination of the position of the most stress point in the ground. This is the topic of the article.

Using the offered new calculation method provides for more substantiated selection of insightful measures to improve strength and deformation characteristics of the ground, for example, with the use of geosynthetic materials.

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