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MODELING OF PARAMETERS OF BEARING CAPACITY OF THE REINFORCED ROAD SURFACE

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Abstract:

The subject of the article is to assess the effectiveness of using the reinforcement system in road construction (surface, foundation, subgrade), treated as the multilayer system of granular soil. In the first part of the paper the authors use analytical models of friable layers of soil with horizontal inserts in order to evaluate the bearing capacity of the reinforced road surface, basing on results of the experimental research realized on physical models on a laboratory scale. The second part takes the form of a diagnosis as regards the possibility of quantitative estimations of the bearing capacity, and provides the bases of procedures aiming at the assessment of the bearing capacity of the reinforced soil by means of advanced methods and approaches in geotechnical engineering and theoretical mechanics.

Keywords:

analytical models, capacity, road surface, soil structure

INTRODUCTION

The maximum (critical) stress, which does not cause the occurrence of the yielding zone at ground level, is commonly assumed as the measure of the bearing capacity of road construction (surface, subgrade) [13]. Modeling the state of effort of the road foundation elements is associated with solving geotechnical problems, while operating one -, two - or multi-parameters ground models [7, 8, 9, 10, 11, 12]. Among the strength parameters of ground, being the measure of bearing capacity, there can be distinguished in particular: California bearing ratio CBR [%] and the strain modulus E_0 [MPa]. Increasing the bearing capacity is a priority in the face of the precipitous modernization of the road network. Methods and means of the soil reinforcement in civil engineering can be generally categorized into two groups: the physical-mechanical and physical-chemical strengthening [13]. The first group includes the land reinforcement or the installation of inserts made from materials having the ability to take over tensile stress. This type of reinforcement of the road subgrade is considered in the article. Inserts, located in the direction of tensile forces, take some of these forces on the basis of cooperation with the ground, depending on the material properties and other factors.

1. THE THEMATIC SCOPE OF THE STUDY

The subject of the article is to assess the effectiveness of using the reinforcement system in road construction (surface, foundation, subgrade), treated as the multilayer system of granular soil. There are analyzed the effects of the physical-mechanical strengthening (reinforcement) with the use of openwork inserts (square mesh) arranged perpendicular to the vertical plane of the load. The structure of inserts and the way of their location satisfy the maximum operational efficiency in terms of reducing vertical and horizontal distortion of the representative element of the road structure. The bases for the assessment are analytical models (based on the results of own research conducted on physical models on a laboratory scale) [8, 9, 11] and the assumptions of numerical procedures (based on advanced methods in geo-technics and theoretical mechanics) aimed to estimate the bearing capacity of the reinforced soil [4, 5, 6].

2. ANALYTICAL MODELS OF ROAD SURFACE STRUCTURE WITH REINFORCEMENT

The model of the stress limit state using Mohr's circles.

The results of the research of the French Road and Bridge Laboratory (Laboratoire Central des Ponts et Chausseess-LCPC) [2, 3] and national centers (the University of Technology in Wrocław, the Institute of Hydroengineering of the Polish Academy of Sciences in Gdańsk, the University of Technology in Gdańsk) [1, 4-12] carried out on physical models on a laboratory scale as well as on analytical models indicate that the non-cohesive soil reinforced bi-directionally with horizontal inserts behaves as if it had the anisotropic cohesion. The cohesion c^* is the effect of the initial tension σ_0, induced by the reinforcement inserts. The cohesion c^* value is given by the following formula:

$$c^* = 0{,}5\, R_T\, (\Delta z)^{-1}\, tg\, (45^\circ + 0{,}5\, \varphi) \tag{1}$$

where:

- RT - the tensile strength of horizontal layers of the reinforcement;
- Δz - the vertical distance between reinforcement layers;
- the angle of internal friction of soil.

One of the most important results of the French research (LCPC) is the analytical presentation of the damage curve of samples of sand reinforced with aluminum foil, tested with the use of the tri-axial apparatus, depicted in the plane of principal stresses σ_1, σ_3 :

$$\sigma_1 = f(\sigma_3) = \sigma_3\, tg^2(45^\circ + 0{,}5\, \varphi) + \sigma_0 \quad (2)$$

where:

- σ_0 - the initial stress being the effect of the reinforcement;
- ϕ - the angle of internal friction of sand.

The equation (2) is, in fact, the analytical model of the road surface structure with reinforcement. The limit state of stresses in the non-cohesive soil, both unreinforced and reinforced, is shown in Figure 1, assuming the constant horizontal stress σ_3 (horizontal resistance of soil) and increasing operational load σ_1.

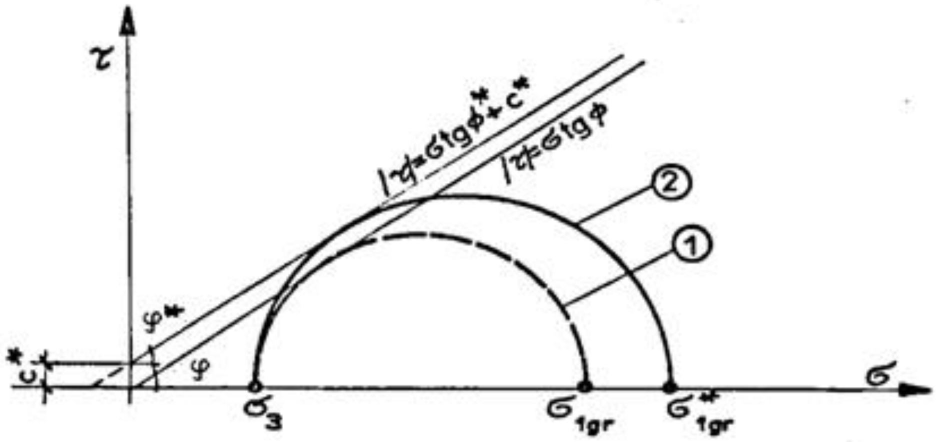

Fig. 1. Illustration of the limit state of stresses in the unreinforced (1) and reinforced (2) non-cohesive soil [11]: ϕ – the angle of internal friction in the unreinforced soil; ϕ^* – the angle of internal friction in the reinforced soil; c^* - the effect of cohesion in the reinforced soil; τ - the shear strength; σ_{1gr} - the vertical principal stress in the limit state of the unreinforced soil; σ_{1gr}^* - the vertical principal stress in the limit state of the reinforced soil; σ_3 – the horizontal stress as a reference point

Source: Own work

Figure 2 shows the effect of the bearing capacity increase of the non-cohesive soil models as a result of the reinforcement, using the Mohr structure. This example comes from the experimental studies of the state of strain of the physical rectangular model (with dimensions in the plan of 0.54 x 0.54 m and the height of 0.42 m) of granular soil reinforced with horizontally localized geo-synthetic inserts TENSAR.

The model of the reinforced road construction describing efficiency of the reinforcement system.

The results of the performed experimental studies [8-11] lead to the conclusion that the function of the reinforcement (polypropylene mesh) in the non-cohesive soil consists of reducing the coefficient of horizontal pressure $K^* = \sigma_2^*(\sigma_1)^{-1}$ 1.

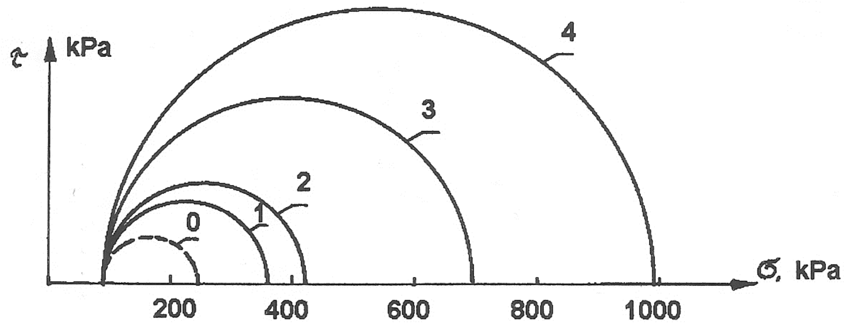

Fig. 2. The effect of the bearing capacity increase of the non-cohesive soil models as a result of the reinforcement [11]: 0 – a model (without reinforcement); 1 – a model reinforced with a single insert; 2 – a model reinforced with two inserts; 3 – a model reinforced with three inserts; 4 – a model reinforced with seven inserts spaced evenly; τ - the shear strength; σ_{1gr} – the vertical normal stress

Source: Own work

The reduction of the coefficient *K* as a result of the reinforcement, adopted as the efficiency parameter of inserts and marked with ΔK, was described by the following formula [8-11]:

$$\Delta K = K - K^{*} = \Delta\sigma_{2,k} (\sigma_1)^{-1} = E\, \mu_c\, W\, (tg\varphi)^{-1} \quad (3)$$

where:

- the angle of internal friction of soil;
- *E* - the Young's modulus of the reinforcement material;
- $\mu_c = n\, \mu_i$ - the total percentage of the reinforcement;
- *n* - the number of inserts of the reinforcement;
- μ_i - the unit percentage of the reinforcement (for a single insert);
- *W* [MPa^{-1}] – the correction coefficient;
- K^{*} - the coefficient of the horizontal pressure in the reinforced soil;
- $tg\varphi$ - the state of soil density.

The model expressed by the practical equation of the strain modulus.

In engineering practices, the bearing capacity of surface and subgrade of roads is estimated on the basis of measurements of vertical strain. Thus, it is appropriate to refer the results of the experimental studies made on physical models of the surface (relating to the state of strain) to the formula used for calculating the strain modulus *E,* based on testing with the use of the apparatus VSS [8, 11, 13]:

$$E_1 = 3\, \Delta p_1\, (4\, \Delta s_1)^{-1} D; \; E_2 = 3\, \Delta p_2\, (4\, \Delta s_2)^{-1} D \quad (4)$$

where:

- E_1, E_2 - respectively, the primary and secondary modules;
- $\Delta p_1, \Delta p_2$ - the load increase, respectively, in the first and second cycles of loading;

- $\Delta s_1, \Delta s_2$ - the increase in vertical displacements, respectively, in the first and second cycles of loading for the load variations within Δp;
- *D = 0,30 m* - the diameter of the measuring plate [13].

The value of the quotient E_2 / E_1 is of great importance, because the quality of technical components of the road construction is specified on the basis of road traffic standards.

The formula (4) was treated as the analytical record of the model of work of the non-cohesive soil layer (constituting the unenriched, gravel or crushed stone, surface or the substructure made of mechanically stabilized aggregate). The equation above could also refer to the reinforced surface structure, after entering the value of the element $\Delta p_1^* > \Delta p_1$ and, similarly, $\Delta p_2^* > \Delta p_2$ (the asterisk indicates the value after applying the surface reinforcement), leaving the values Δs_1 and Δs_2 unchanged.

3. THE ESTIMATION OF THE BEARING CAPACITY OF REINFORCED SOIL USING THE THEORY OF THE ULTIMATE LIMIT STATES

This issue is discussed in the handbook [4] as the so-called simple estimation of the bearing capacity with reinforcement. The authors of the quoted publications lead analysis using the yield condition, after taking into account the thesis proven in the work [1] based on the results of the experimental studies conducted at the Institute of Hydroengineering of the Polish Academy of Sciences (IBW PAN - Gdańsk). The mentioned thesis concerns the loss of the bearing capacity of reinforced soil as a result of yielding two components: the soil and the reinforcement inserts in the immediate vicinity of the foundation, that is, by analogy, in the subgrade under the construction of the road. Based on the approved task scheme (Figure 3), the handbook [4] gives the conduct of proceedings leading to the solution in the form of the formula, which allows for the estimation of the value of the limited bearing capacity (φ is the angle of internal friction of soil:

$$p_{gran} = 0{,}5\sigma_0 \,[1+ (\sin\varphi)^{0,5}]^2 \,(1 + \sin\varphi)\,(1 - \sin\varphi)^{-1} \tag{5}$$

where:

- the angle of internal friction of soil;
- $\sigma_0 = \mu_c R_T$ - the stress resulting from the reinforcement of soil;
- μ_c - the total percentage of the reinforcement (as in the formula 3);
- R_T - the tensile strength of horizontal layers of the reinforcement.

4. THE STATIC SOLUTION TO THE PROBLEM OF THE BEARING CAPACITY OF THE REINFORCED SOIL

The static solution to the bearing capacity of soil, reinforced with inserts spaced evenly in the horizontal plane (perpendicular to the plane of the operational load), using the method of characteristics, was developed - as the simple estimation indicated above - at the Institute of Hydroengineering of the Polish Academy of Sciences (Gdańsk) [4]. The quoted handbook gives the conduct of proceedings (with the application of the numerical technique) after having the below listed auxiliary developments performed:

- drafting the task scheme, being the half-space from the reinforced soil, loaded with the band with the fundamental intensity p and the width b as well as the symmetrical additional evenly distributed vertical load q, the aim of which is to eliminate the local uncertainty of a solution (Figure 4);

- designing the grid of characteristics of stresses in the areas of the compressive reinforcement;
- defining the grid of characteristics of stresses in the area of the rigid reinforcement;
- limiting the area of the rigid reinforcement to one line.

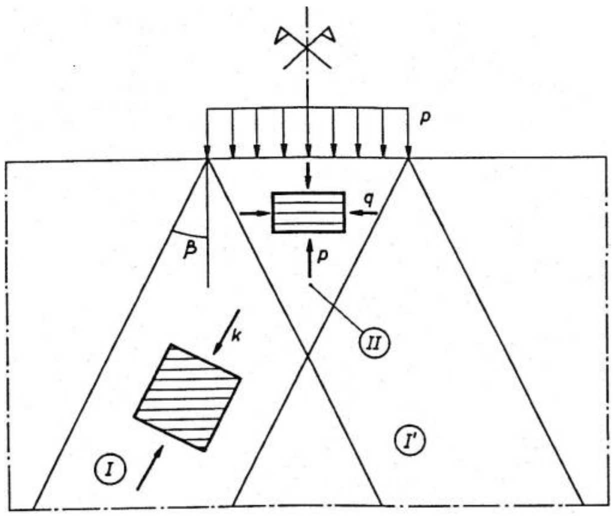

Fig. 3. The task scheme – the field of stresses in the reinforced soil [4]:
I, I' – the 1-axel stress field;II - the 2-axel state of stress;
p – the vertical stress; q – the horizontal stress, the boundary lines of zones I; I', II are the stress discontinuity lines

Source: Own work

Then, using the procedure according to the handbook [4], which involves solving differential equations of balance and the yield condition, the following formula to calculate the value of the limited bearing capacity is obtained:

$$p_{gran} =(1+\sin\varphi) \{q(1-\sin\varphi)^{-1}+\sigma_0 [\exp(0,5\pi-\varphi)\mathrm{tg}\varphi]^{-1}\} \exp(\pi tg\varphi) \qquad (6)$$

where:

- the angle of internal friction of soil;
- σ_0 - the stress taken over by the reinforcement;
- q - the additional evenly distributed vertical load.

In the considerations the limited bearing capacity is treated as the minimum value of the force *P* that is necessary to escalate substantial plastic deformations, unacceptable in view of the construction safety.

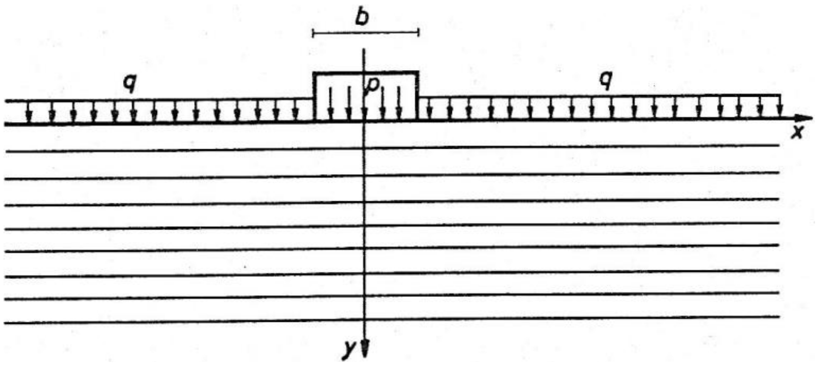

Fig. 4. The task scheme: the half-space of the reinforced soil loaded with the band with the intensity p and the width b [4]: q - the additional evenly distributed vertical load.

Source: Own work

CONCLUSION

The bearing capacity, estimated on the basis of analytical models prepared on the grounds of results of own experimental studies of the spatial state of stress and the strain of the non-cohesive reinforced soil, realized on physical models on a laboratory scale, is determined by the parameters:

- the anisotropic cohesion σ_0 triggered by the reinforcement; the angle of internal friction φ and the normal stress σ_1 (in the "stress" model using the structure of Mohr's circles);
- the reduction of the coefficient of horizontal pressure ΔK (in the model based on the parameter determining the participation of the reinforcement system in limiting distortion of the soil - matrix);
- the vertical displacement Δs_i (in the model expressed by the equation of the strain modulus) and the value of the strain modulus E resulting from displacements.

The programmed tasks presented in the article aim to estimate, using the procedures arising from the advanced methods of geotechnical engineering and theoretical mechanics, the values as follows:

- the limit load q_{gran} using the claim of the assessment of the lower limit load;
- the bearing capacity of the reinforced soil p_{gran} using the method of characteristics.

The variability of the above parameters of the models determines the value of the bearing capacity of the reinforced soil.

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BIOGRAPHICAL NOTES

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