KOMUNIKÁCIE
COMMUNICATIONS

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VYBRANÉ PROBLÉMY MECHANIKY SPEVNENÝCH ZEMÍN

SELECTED PROBLEMS OF REINFORCED SOIL MECHANICS

Uvádzajú sa vybrané problémy mechaniky sypkého zemného prostredia, na príklade výskumu zmeny tvaru pravouhlých vzoriek zaťažených zvislým statickým osovo-symetrickým tlakom. Vzorky boli vystužené vodorovne rozmiestnenými sieťkami. Popisuje sa spolupôsobenie elementov spevnenej zeminy, menovite charakteristiky vzájomného vplyvu zemného prostredia a spevnenia na rozmer pásma spolupôsobenia.

Pri hodnotení vplyvu spevnenia zemného prostredia bolo uvažované stredné vodorovné napätie a odvodený koeficient bočného tlaku.

Selected problems of the mechanics of a loose soil medium, illustrated with tests of cuboidal specimens loaded with a vertical, static, axial symmetric pressure, have been presented. The specimens were reinforced with inserts (nets) situated horizontally, i.e. perpendicular to the plane of loading. The interaction between reinforced soil components, in particular the influence of soil and reinforcement related factors on the size of an interaction zone, was discussed.

An average horizontal stress and an experimental coefficient of lateral pressure were taken into account when assessing the effect of reinforcement on the deformability of soil.

1. Introduction

Reinforced soil has been used as material in various civil engineering structures for over 30 years. The introduction of soil reinforcement into engineering practice opened up a new field: reinforced soil mechanics, covering three major groups of problems: proper choice of reinforcement, description of the mechanical properties of a considered composite material and the interaction between a reinforced-soil structure and the medium [5].

The Polish Academy of Sciences Institute of Hydro-Engineering in Gdańsk has contributed significantly to the development of reinforced soil mechanics [2, 4, 5] by creating rigid-elastic and elastoplastic models of reinforced soil, working out the slope's and the retaining wall's load bearing capacity and the static and kinematic solutions of the limit load capacity of loose subsoil loaded with foundations, etc.

In laboratory testing three main areas relating to: the reinforcement's mechanical properties, the interaction between reinforced soil components and the testing of reinforced soil treated as a composite can be distinguished [5]. As is stated in handbook [5], divergences of opinion about a proper theoretical approach to reinforced soil's function can be successfully settled through experimentation.

This paper deals with an experimental analysis of the behaviour of large-size specimens of reinforced loose soil (a laboratory model) loaded vertically with a static pressure. The vertical (settlement) and horizontal (lateral pressure) deformations were measured and the performance of the reinforcement and changes in the values of the soil specimen's mechanical properties versus the adopted parameters relating to the test conditions (load), the soil medium (compaction), the number and location of reinforcing inserts were assessed. The reinforced subsoil behaviour model consists of: coarse river sand and horizontally placed plastic nets (denoted by ST) and steel net (denoted by SS) with a mesh size of 30 × 30 mm. The soil specimens were tested in two states of compaction: as loosely heaped up sand (1st loading cycle) and precompacted soil (9th loading cycle). The cuboidal test specimens were placed in a 0.54 × 0.54 m in plane and 0.42 m high container. Seven model wall measurement levels were distinguished: $z_1 = 0.03$ m; $z_2 = 0.09$ m; $z_3 = 0.15$ m; $z_4 = 0.21$ m; $z_5 = 0.27$ m; $z_6 = 0.33$ m; $z_7 = 0.39$ m.

2. Interaction between reinforced soil components

Under vertical static loading $q = 0.24$ MPa the lateral pressure of reinforced loosely heaped up sand along the model's height as a function of the number of net ST inserts is as shown in Fig. 1. A single reinforcement at measurement level z_4 (curve 1), a double (two nets) reinforcement at depth $z_{3/4} = 0.18$ m and $z_{5/6} = 0.30$ m; a triple reinforcement at levels z_2, z_4 and z_6 and a multilayer reinforcement (spaced evenly at every $\Delta = 0.06$ m along the height) at levels z_1, z_2, z_3, z_4, z_5, z_6, z_7 were used.

The tests were comparative in nature: the results were compared with the results obtained for reference specimens, i.e. unreinforced sand.

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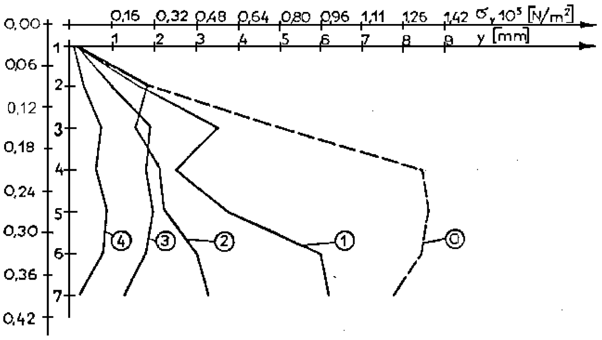

Fig. 1. Graphs of horizontal sand specimen pressure as function of number of reinforcing inserts; 0 - specimen without reinforcement (reference standard), other denotations in text.

A reinforcement influence zone, i.e. a zone of insert influence on soil grains, is visible in the graphs. Previously carried out laboratory tests showed that the extent of this zone depends on:

- the magnitude of the external load (reinforcement is a passive component and it begins to interact with soil grains as a result of loading) and the history of loading,
- the kind of inserts (the mesh size of the nets, the tensile strength of the material) and their location.

The medium-reinforcement interaction is satisfactory if the insert does not stratify the soil, is rigid enough, resists pulling out and is situated in the zone where maximum lateral pressure data occur. It has been found that if the medium is reinforced with two or more inserts, it is possible to control the deformability of the models by changing the location of the individual inserts. Even slight vertical dislocations of the inserts are reflected in the redistribution of horizontal earth pressure. If two inserts are situated too close to each other, the resulting earth pressure distribution is similar to that characteristic of soil reinforced with one net. In extreme cases, the effects may be even worse (loss) than for a single reinforcement.

3. Effect of reinforcement on soil deformability

An average horizontal stress and an experimental coefficient of lateral pressure were used to determine the effect of reinforcement on soil deformability. The state of limit active pressure (resulting from load $q = 0.24$ MPa) was deemed proper for the analysis of the behaviour of reinforced soil. Experimental investigations showed a state of static pressure in the (loosely poured) sand specimens not subjected to loading.

Graphs of the average horizontal stress in sand specimens reinforced with one ST net, two nets, three nets or seven nets are shown in Fig. 2. The location of the reinforcement is the same as in Fig. 1.

Experimentally determined horizontal stresses $\sigma_{\acute{s}r}$ were used to determine the experimental coefficients of lateral pressure for specimens with and without reinforcement (fig. 3):

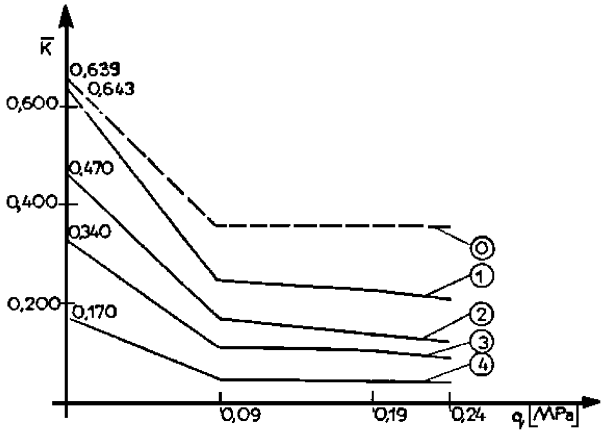

Fig. 2. Graphs of average horizontal stress in specimens of loosely heaped up sand reinforced with ST nets. Commentary in text.

$$K = \sigma_{y,\acute{s}r} \cdot (\sigma_z)^{-1}; K^* = \sigma^*_{y,\acute{s}r} \cdot (\sigma_z)^{-1} \quad (1)$$

where: $\sigma_{y,\acute{s}r}$ - an average horizontal stress in soil without reinforcement, $\sigma^*_{y,\acute{s}r}$ - an average horizontal stress in reinforced soil, σ_z - vertical stress determined in a simplified way on the basis of experiments.

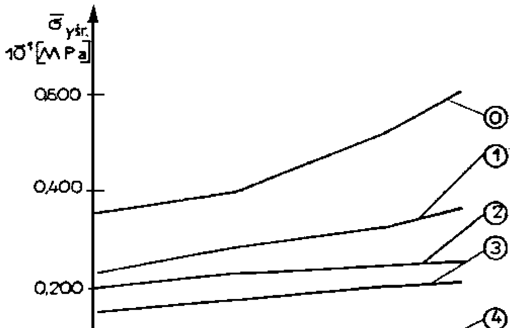

Fig. 3. Experimental coefficient of horizontal pressure for loosely heaped up sand reinforced with ST nets as function of number of inserts. Load $q = 0.24$ MPa. Symbols: 0 - reference standard, 1 - single net at level z_4, 2 - two nets at levels $z_{3/4}$ and $z_{5/6}$, 3 - three nets at levels z_2, z_4 and z_6, 4 - seven nets vertically spaced at every $\Delta z = 0.06$ m.

The following conclusions emerge from the authors' investigations:

- As the load increases, the pressure coefficient values in a specimen of loosely heaped up sand and precompacted sand approach a certain constant, which they can reach when the upper limit of the applied load is exceeded. This applies to sand with and without reinforcement. The value which coefficients K and K^* approach is the lower, the more precompacted (i.e. subjected to loading and unloading cycles) the sand was. For upper limit load $q = 0{,}24$ MPa:

$$K^{IX} < K^{I} \text{ and } K^{*IX} < K^{*I} \tag{2}$$

- For reinforced sand the lateral pressure coefficient values are markedly lower than for (precompacted or loosely heaped up) unreinforced sand:

$$K^{*I} < K^{I},\ K^{*IX} < K^{IX} \tag{3}$$

It is proposed to determine coefficient K^* as function $K^* = f(\lambda, m_z, r_z)$ where λ is a reinforcement material parameter (e.g. Young's modulus or Poisson's ratio), m_z – the amount of reinforcement in the soil medium, r_z – the spacing of the reinforcement along the height of the soil layer (spacing Δz of inserts or the depth at which insert z_k is situated in the case of a single reinforcement).

4. Reinforced soil behaviour model – proposal of analytical representation

Reinforcement favourably affects the soil medium's material characteristics, taking over some stresses σ_2 produced by lateral pressure. The taken over part of the stresses in the horizontal plane, expressed as $\Delta\sigma_{2,k}$, is directly proportional to original stress σ_2 (i.e. in unreinforced soil):

$$\Delta\sigma_{2,k} = f(\sigma_2),\ \ 0 \le \Delta\sigma_{2,k} < \sigma_2 \tag{4}$$

In a particular soil medium, stress $\Delta\sigma_{2,k}$, further referred to as "compressing" stress, generally depends on: the magnitude of the load, the loading history and the reinforcement's parameters. Two main variants of the state of stress in reinforced soil are proposed for the theoretical model.

Variant 1. It is assumed that the soil medium's parameters do not change. The specimen is in three-dimensional state of principal stress: σ_1 (vertical stress induced by loading) $> \sigma_2 = \sigma_3$ is a horizontal stress induced by the passive pressure of the neighbouring zones of the soil medium. It is assumed that the reinforcement causes an increase of $\Delta\sigma_{2,k}$ (compressing a soil element) in the horizontal stress resulting from the passive pressure of the adjacent zones of the medium. Thus the passive-pressure stress acting on a reinforced soil element (the equation of the reinforced soil behaviour model) is as follows:

$$\sigma_2^* = \sigma_2 + \Delta\sigma_{2,k} \tag{5}$$

Variant 2. The part of stress σ_2 taken over by the reinforcement is $\Delta\sigma_{2,k}$ and the model equation (a relation for calculating horizontal stress in a reinforced-soil element) is as follows:

$$\sigma_2^* = \sigma_2 - \Delta\sigma_{2,k},\ \ 0 \le \Delta\sigma_{2,k} < \sigma_2 \tag{6}$$

The two hypothetical models can be presented graphically using limit Mohr's circles (relating to limit states of active earth pressure) in a medium with and without reinforcement.

5. Material parameters of reinforced soil

The basic strength features of a reinforced soil medium include: modulus of elasticity E_0^* internal friction angle φ^*, anisotropic cohesion c^* (according to [3, 6]) and coefficient of lateral pressure K^*.

In the limit state of active earth pressure value *the following relation can express K*:

$$K^*_{min} = K_{min} - \Delta K_{max} = tg^2(45° - 0.5\varphi) - \Delta K_{max} \tag{7}$$

where: ΔK_{max} is a reduction in the coefficient of lateral pressure owing to reinforcement. The N.T. Long and F. Schlosser formula [3], which defines the anisotropic cohesion of reinforced soil, has this form:

$$c^* = 0.5 \cdot R_r(\Delta z)^{-1} \cdot tg(45° + 0.5\varphi) \tag{8}$$

where: Δz – the vertical spacing of the planes of reinforcement, R_r – a unit tensile strength of a reinforcement plane [N/m].

After the transformation of the basic equation of principal stress in the limit state of active earth pressure (derived from the theory of limit states) and the substitution of expression (8) we get:

$$K_{min} = tg^2(45° - 0.5\varphi) - cos\varphi^* \cdot [(1 + sin\varphi^*) \cdot \\ \cdot \sigma^*_{1,gran} \cdot \Delta z]^{-1} \cdot R_r \cdot tg(45° + 0.5\varphi) \tag{9}$$

Taking into account the results of model tests carried out by the author [7, 8, 9, 10], the effects of reinforcement were expressed by parameter ΔK:

$$\Delta K = (tg\varphi)^{-1} \cdot E\mu \cdot g(n) \tag{10}$$

where: $g(n) = W$ is a correction factor (describing the experiment-theory relationship) having a functional form.

Adopting a distance sum square minimum as the criterion for the selection of function $g(n)$, the latter was defined as power dependence $g(n) = \eta\sqrt[3]{n}$ where n is a number of horizontal reinforcement layers. Then formula (10) assumes this particular form:

$$\Delta K = (tg\varphi)^{-1} \cdot E\mu\eta \cdot \sqrt[3]{n} \tag{11}$$

In the literature on soil mechanics one can find relations for the internal friction as a function of soil compaction degree I_D, e.g. the Szaraniec or Weissenbach formulas [1]. When the Weissenbach relation is put into formula (11), we get:

$$\Delta K = (0.58 + 0.5I_D)^{-1} \cdot E\mu\eta \cdot \sqrt[3]{n} \tag{12}$$

The following exponential relation can describe the above formula as a function of the degree of soil compaction: $y = ba^x$. If the parameters in formula (11) are assumed to have the following values: percentage of reinforcement $\mu = 0.384$, factor adjusting experimental results to those obtained from formula (10) $W = g(n) = 1.0 \cdot 10^{-5}$ [MPa]$^{-1}$, the reinforcing insert's Young's modulus $E = 2{,}1\ 10^5$ MPa, then this relation assumes the following particular form:

$$\Delta K = f(I_D) = 1.389 \cdot a^x \qquad (13)$$

Allowing for the possibility of introducing number m of degrees of soil medium compaction (in range $I_D = 0.0 - 1.0$), a set of base-of-power values $a = 1.0 - 0.537$ is obtained. If formula (13) is to be fairly universal, average value $a_{śr} = 0.491$ should be assumed.

Reinforcement effectiveness ratio ΔK for specimens of different kinds of loosely heaped up and precompacted soil depending on number $n = 1 - 7$ of reinforcing inserts (nets ST) is shown in Fig. 4.

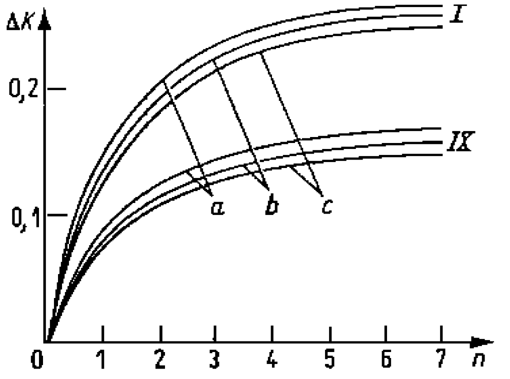

Fig. 4. Parameter ΔK for soil specimens depending on number $n = 1 - 7$ of reinforcing nets ST. Consistency of loosely heaped up soil (I) and precompacted soil (IX): a - sand, b - valley gravel, c - basaltic grit.

The anisotropic cohesion of reinforced soil leads to increased shear strength defined by the following equation [11]:

$$\tau_f = p_z \cdot tg\varphi + c \qquad (14)$$

in which, acc. to [3, 4, 6], for reinforced soil:

$$p_z = p_y\, tg^2(45° + 0.5\varphi) + p_0 \qquad (15)$$

p_y - vertical stress (perpendicular to a plane of reinforcement),
p_0 - additional horizontal stress in the state of damage of a reinforced soil specimen, expressed by this relation:

$$p_0 = 2c \cdot tg(45° + 0.5\varphi) \qquad (16)$$

If the settlement of a reinforced soil specimen is Δh and it is caused by vertical compressive stress p_2, effective strain E_0 is expressed by:

$$E_0 = p_z h(\Delta h)^{-1} \qquad (17)$$

a soil (sand) specimen's strength parameters as a function of the quantity of reinforcement measured by percentage μ are presented in Fig. 5.

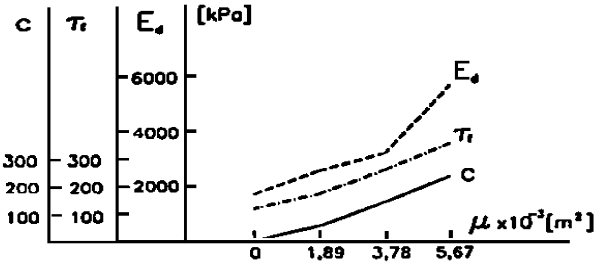

Fig. 5. Soil specimen's strength parameters as function of reinforcement quantity (μ - percentage of reinforcement); c - cohesion, τ_f - shear strength, E_0 - modulus of elasticity.

6. Conclusion

Selected problems of the mechanics of a loose soil medium, illustrated with tests of cuboidal specimens loaded with a vertical, static, axial symmetric pressure, have been presented. The specimens were reinforced with inserts (nets) situated horizontally, i.e. perpendicular to the plane of loading.

The interaction between reinforced soil components, in particular the influence of soil and reinforcement related factors on the size of an interaction zone, was discussed.

An average horizontal stress and an experimental coefficient of lateral pressure were taken into account when assessing the effect of reinforcement on the deformability of soil. The limit state of active pressure was adopted for the analysis of the behaviour of reinforced soil specimens. From empirical observations conclusions regarding the coefficient of lateral pressure in a reinforced soil specimen were drawn.

Two versions of a reinforced soil behaviour model were considered and an analytical representation was proposed for them. Taking account of the experimental results, relations for the calculation of:

- lateral pressure coefficient K in a limit active state and
- reinforcement effectiveness expressed by reduction ΔK of the pressure coefficient (for variable features of the soil and the reinforcement inserts)

were derived.

The graph of soil specimen strength parameters versus percentage of reinforcement demonstrates the widely recognized (for over thirty years) advantages of reinforced soil.

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