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Parameter of Cooperation of Composite Components in Views about Vertical Wall from Reinforced Soil

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The publication considers reinforced soil in relation to the construction of retaining walls in communication construction. The basic elements determining the cooperation of reinforcement inserts with the ground centre are discussed, depending on the features characterizing the components of the composite. The method and selected results of tests performed on a massif model with a vertical wall made of non-cohesive ground have been presented. A calculation example is given concerning the internal dimensioning of the reinforcement of the considered massif model, assuming the work of inserts without slipping in the ground centre. The concept of reinforcement co-operation indicator with the ground centre was introduced and a dependence to calculate its value was developed. The values of co-operation indicators: general and partial, concerning individual measurement levels of the model have been presented appropriately.

Keywords: reinforced soil, reinforcement dimensioning, cooperation indicator, model research.

1. ELEMENTS OF REINFORCEMENT COOPERATION WITH A GROUND CENTRE

When designing reinforced structures with reinforced soil economically, special attention should be paid to ensuring proper interaction of the inserts with the ground centre [2, 4-8, 12-14]. The quality of this cooperation has a significant impact on the bearing capacity of the structure, which determines the possibilities of carrying out operational loads. The parameters of reinforcement (material type, tensile strength, stiffness, spatial shape, number of inserts) depend on the size of friction forces between ground grains and reinforcement and the resistance value on displacement of inserts in the ground material. The cooperation of the insert formed in the form of a lattice or grid with a ground centre is based on the occurrence of two phenomena [1-4, 16-20]: friction (Fig. 1a), and shearing of the soil medium (delamination) under the conditions of transversely locating the rods to the direction of acting forces horizontal T (Fig. 1b).

Regarding the research on the phenomenon of friction, one should note the significant experience of the Central Laboratory of Roads and Bridges (Laboratoire Central des Ponts et Chaussées - LCPC) in Paris (e.g. [1, 3, 9-11, 15]). Measurements on models and real objects have shown that the tensile stresses are variable over the length of the inserts. If σ_1 is a vertical compressive stress in the ground acting in the plane of reinforcement, then the normal force for the dN insert (force of the double "pressure") on the length dl on both flat surfaces of the insert is:

$$dN = 2\ \sigma_1\ b\ dl \qquad (1)$$

where:
b - the width of the insert,

while for a circular insert:

$$dN = \pi\ \sigma_1\ d\ dl \qquad (2)$$

where:
d is the diameter of the rod.

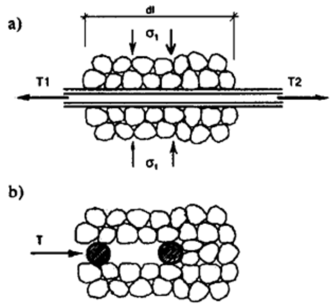

Fig. 1. Factors determining the cooperation of reinforcement with non-cohesive soil [9, 10]: a - friction, b - lateral displacement resistance

This relationship should be treated as formulated correctly assuming the same tangential stress τ, originating from the ground on both surfaces of the insert. Because the friction on the contact is promoted, the ground-reinforcement centre eliminates slippage, the following applies:

$$dT\,(2\,\sigma_1\,b\,dl)^{-1} \leq f \qquad (3)$$

where:

f - coefficient of friction between ground grains and reinforcement,

dT - change of tensile force over the length of the insert dl.

In the case of a limiting equilibrium, the formula (3) gets the form (after entering the safety factor $k > 1$):

$$dT = 2\,\sigma_1\,b\,dl\,f\,(k)^{-1} \qquad (4)$$

Considering the second phenomenon, characterizing the cooperation of the soil centre with reinforcement, it should be defined by the resistance of insert displacement in the deformations of the loaded reinforced soil layer. This resistance depends on from the degree of spatial shape of the insert.

French research [1, 3, 9-11, 15] also showed that the sample of the non-cohesive medium behaves as if it contained anisotropic cohesion, the value of which is a function of the quality of the cooperation of inserts with the ground centre. The curve of soil sample destruction with horizontal layer reinforcement (obtained as a result of laboratory tests) can be approximated with a simple equation:

$$\sigma_1 = \sigma_3\,\mathrm{tg}^2\,(0{,}25\,\pi + 0{,}5\,\varphi) + \sigma_0 \qquad (5a)$$

where:

φ - the angle of internal friction of the ground,

σ_0 - initial stress, which is a function of reinforcement strength R_r, vertical distance of reinforcement layers e_z and mechanical properties of the soil medium (characterized inter alia by the angle of internal friction φ).

The occurrence of stress σ_0 indicates the anisotropic coherence c^*, determined by the relationship developed in the LCPC [9, 10, 15]:

$$c^* = f_a\,\mathrm{tg}\,(45^0 + 0{,}5\,\varphi)\,(2\,\Delta z)^{-1} \qquad (5b)$$

where:

f_a - strength of horizontal layers of tensile reinforcement [kN / m-2],

φ - angle of internal friction of soil material [º],

Δz - vertical distance of reinforcement layers [m].

2. DESCRIPTION AND RESULTS OF MODEL TESTS OF THE EFFICIENCY OF REINFORCING RETAINING STRUCTURES

• Test method

Experimental work was carried out on a laboratory ground massif model located in a rectangular container with the dimensions shown in Figure 2 [16-20]. The subject of the research are horizontal displacements of the loaded massif, measured in the vertical plane of the model's wall. On the basis of displacements, the size of the fracture body in the limit state of the active ground pressure was estimated. The ground centre is dry coarse sand, characterized by physical parameters: volumetric weight in loosely poured condition γ_0 = 19.0 kN / m3, natural humidity w_n = 0.3%, density of loosely poured sand I_D = 0.38 and angle of internal friction φ = 30.20 (determined for a sand sample in a laboratory direct shear apparatus). Reinforcement inserts in the form of strips of length l_a = 1.80 m, made of 50HSA hardened spring steel were placed horizontally at a vertical distance e_z = 0.195 m. In each layer, the strips were located parallel to the longitudinal axis of the container, maintaining the same horizontal distances, which were accepted respectively: e_x = 0.11; 0.17 and 0.23 m. The following methods of tape reinforcement were designed (with a smooth or spatially shaped surface using special "notches") in individual tests:

- method A (5 layers of 9 inserts in a layer, including $n_{a,c}$ = 45 inserts, e_x = 0.11 m),
- method B (5 layers with 6 inserts, total at, $n_{a,c}$ = 30 inserts, e_x = 0.17 m),
- method C (5 layers of 4 inserts, total at, $n_{a,c}$ = 20, e_x = 0.23 m).

The assumed vertical load of the ground massif model results from the research method and is mainly the factor initiating the generation of the fragment body.

The load was carried out in a static manner, by means of a horizontal rectangular rigid panel with dimensions of 0.15 x 1.0 m - Fig. 2) located transversely to the horizontal, longitudinal axis of the model. The minimum distance of the edge of the panel from the inner surface of the front wall was taken as l_y = 0.30 m. The same load value (in the range of 0-61.69 kPa) was used for all tests and at the same time the minimum but necessary to produce a fragment of the mass in the ground mass model with reinforcement . The analysis of the course of horizontal strains of the models concerned two conditions of soil massif consolidation: loosely poured (*l.s.*) and pre-compacted surface (*w.z.p.*).

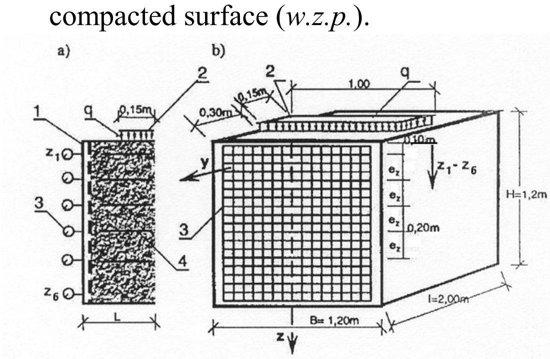

Fig. 2. Scheme of the test stand [19, 20]: a - fragment of vertical section, b - general view, 1 - retaining wall (measuring) of the model, 2 - load plate with dimensions of 0.15 x 1.0 m; 3 - horizontal displacement sensors, 4 - reinforcement inserts; z_1, z_2, z_3, z_4, z_5, z_6 - measurement levels.

• Findings

On the basis of the measured horizontal displacements of the massif model, unit horizontal dust pressure $p_y(z)$ in the plane of the front measuring wall was calculated (with depth). After integrating the dust surface $p_y(z)$ at the height of the wall H $\{P_y = \int p_y\,(z)\,dz, H = 0,0\text{-}1,20\}$, the total horizontal pressure of soil unreinforced P_y and reinforced P_y^* was obtained.

The W_{py} index was calculated as the ratio of the total horizontal pressure P_y^* to the P_y load value, characterizing (in percentage size) the degree of reduction of soil pressure due to the installation of reinforcement inserts (Table 1, Fig. 3) [20]:

$$W_{Py} = [100 - P_y^* \,(P_y)^{-1}\, 100],\ \% \qquad (6)$$

The value of the W_{Py} ratio increases with increasing load, which indicates that the reinforcement is a passive element and undertakes cooperation as a result of the load. Table 1 and Fig. 3 show that in reinforced sand with notched tapes, the effects of reinforcement consisting in the reduction of horizontal pressure are practically independent of the change in soil compaction (in the range introduced in the tests). In the sand reinforced with strips without notches, subjected to the initial compaction load, the effects of reinforcement decrease by approximately 30%.

The dimension of the cooperation of the notch inserts with the pre-compacted soil material can be significantly reduced due to the undesirable slip phenomenon. This problem can be reduced or completely eliminated by using retaining elements (so-called notches), increasing the friction value on the contact between the reinforcement plane and the grains of the ground material. In this way, the effectiveness of the reinforcement insert is increased. Therefore, it can be stated that in order to obtain the designed horizontal ground pressure reduction, a correspondingly smaller number of notched inserts can be used than the same inserts that do not contain resistance elements (Fig. 3). From the graphs in this figure, it can be seen that assuming a reduction in the horizontal pressure in the model, e.g., W_{Py} = 30%, the wear of tapes with an area without notches is more than twice as large as the number of notches with notches required.

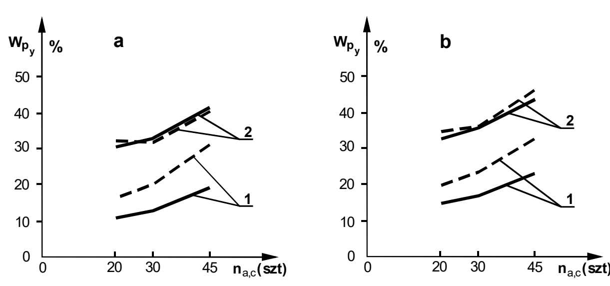

Fig. 3. The index of horizontal pressure reduction of the ground embankment on the retaining wall of the model, as a function of the amount $n_{a,c}$ of reinforcement [20]: a - load q = 37.02 kPa, b - q = 61.69 kPa, - - - sand loosely poured, --- pre-compacted by surface, 1 - tapes without notches (W_{Py}), 2 - tapes with notches (W_{py})

Table 1. The W_{Py} Indicator of the reduction in the horizontal pressure of the ground embankment on the retaining wall of the model [20]. Markings: *l.s* - loosely poured, *w.z.p* - pre-compacted, $n_{a,c}$ - total number of reinforcement inserts in the mass.

Type of reinforcement	Reinforcement method	The amount of reinforcement $n_{a,c}$ [pcs.]	Load ***q*** [kPa] of the ceiling of the model implemented with a 0.15 x 1.0 m board			
			37,02		**61,69**	
			Wp_y Indicator [%]			
			l.s.	***w.z.p.***	***l.s.***	***w.z.p.***
Tapes without notches	*A*	45	30.95	19.48	32.60	23.01
	B	30	20.05	12.90	22.90	16.60
	C	20	16.18	11.16	19.87	14.60
Tapes with notches	*A*	45	40.14	40.72	45.30	42.53
	B	30	31.86	32.29	36.07	35.06
	C	20	31.43	30.96	33.99	32.80

3. CALCULATION EXAMPLE - DIMENSIONING OF THE REINFORCEMENT CROSS-SECTION

The example concerns the estimation of the necessary number of inserts in the cross-section of the modelled mass of non-cohesive soil (coarse sand) with a vertical wall. The load with its own weight and banded research pressure is 61.69 kPa. Mass height H = 1.20 m (laboratory model shown in Fig. 2), vertical spacing of reinforcement layers e_z = 0.195 m. Bulk weight of the soil material in the research container γ_0 = 19.0 kN / m3.

The calculation assumptions have been adopted:

1. The measuring wall of the model (Fig. 2) is kept steady (no horizontal wall displacement and rotation relative to the lower or upper edge).
2. Reinforcement should take over the total horizontal force, which comes from the pressure of the ground wedge on the measuring (resistance) wall of the model.
3. Reinforcement inserts (tapes) that do not contain resistance elements (notches) work in a soil centre without slip (theoretical condition).
4. Computational strength of tensile reinforcement steel f_d = 250 MPa, belt thickness g_a = 0.001 m, belt width (in two variants): b_a = 0.024 m / 0.012 m.

The allowable force taken over by a single insert is calculated from the formula [11, 20]:

$$T_{r,\,d} = b_a\, g_a\, f_d\, (S_r)^{-1} \tag{7}$$

The value of this force after adopting the safety factor S_r = 3.15 is successively: 1.90 kN when b_a = 0.024 m and 0.95 kN for b_a = 0.012 m. The number of n_a^w inserts per 1 m of a single layer length was calculated from the condition:

$$n_a^w\, T_{r,d} = P_{y,z}^w \tag{8}$$

where:

$P_{y,z}^w$ is the value of the horizontal pressure of the ground mass, per one layer of reinforcement.

The results of calculations can be found in table 2 [20].

Depth and layer number of the reinforcement z_k [m]	I				II			
	n^w_a from the formula (8) for b_a [m]		Assumed n_a^w		n_a^w from the formula (8) for b_a [m]		Assumed n_a^w	
	0.024	0.012	0.024	0.012	0.024	0.012	0.024	0.012
z_1 = 0.095	1.81	3.63	2	4	1.16	2.31	2	3
z_2 = 0.290	3.44	6.88	4	7	2.67	5.36	3	6
z_3 = 0.485	3.83	7.65	4	8	3.30	6.61	4	7
z_4 = 0.680	3.12	6.24	4	7	2.22	4.44	3	5
z_5 = 0.875	2.50	5.01	3	5	1.52	3.04	2	3
z_6 = 1.070	2.43	4.86	3	5	1.17	2.34	2	3
Total number of inserts in the massif is $n_{a,c}$:			20	36	$n_{a,c}$:		16	27

4. QUALITY INDICATOR OF REINFORCEMENT COOPERATION WITH SOIL MATERIAL

Based on the results of the calculations contained in table 2, it can be concluded that the total force of pusher forces $P_{y,sw}$, e.g. in loose ground loose mass transfers 20 inserts of width ba = 0.024 m without notches (assuming that the reinforcement works without slipping). Experimental tests (eg [17, 18, 20]) showed, however, that an identical number of these inserts, in the same massif and test conditions, causes a much smaller reduction of pressure, with reference to the pressure of the unreinforced massif (Table 1: reinforcement method C, massif loosely poured, stamp load q = 61.69 kPa, W_{Py} ratio = 19.87%). It follows that in practice the reinforcement works with considerable slip. So you can write a general dependence [20]:

$$W_a \cdot W_{py} \cdot P_{y,sw} = n_{a,c} \cdot T_{r,d} \qquad (9)$$

where:

$W_a > 1$ - general indicator of cooperation of soil material with reinforcement due to taking over tensile forces by reinforcement (regarding the total amount of reinforcement $n_{a,c}$),

W_{py} [%] - percentage reduction of ground pressure due to reinforcement (table 1),

$P_{y,sw}$ - total thrust of the wedge of the wedge in the unreinforced ground mass [kN / m],

$n_{a,c}$ - total number of inserts in 1 meter of the massif length (the width of the research container is taken as 1 m of the massif length),

$T_{r,d}$ - allowable force that a single reinforcement insert can take.

W_a indicator is a measure of the quality of the reinforcement system-ground centre cooperation. It is a function of many variables and depends mainly on the resistance to the horizontal displacement of the reinforcement inserts in the ground centre. Under conditions of perfect cooperation, i.e. no slippage (theoretical case), the W_a indicator receives a value of 1.0 and a W_{Py} = 100% and the reinforcement takes over the entire thrust force $P_{y,sw}$. Then the formula (9) takes the form [20]:

$$P_{y,sw} = n_{a,c} \cdot T_{r,d} \qquad (10)$$

The values of the W_a = 1.0 indicator are appropriate for the total numbers of inserts for c, calculated in Table 2, and the coefficient of the $n_{a,c}$ inserts for the reinforcement coefficients with the ground centre for the individual reinforcement layers $w_{a,z}$ = z = 1.0.

Fig. 4 and Table 3 [20] show values of the general W_a indicator, related to the whole massif model for three reinforcement cases (systems A, B, C). W_a indicators were calculated according to the formula (9), taking as a basis the total force of $P_{y,sw}$, the wedge pressure, estimated as the result of laboratory tests (eg [17, 18, 20]) and the effectiveness of the W_{py} reinforcement work (table 1). The research on $P_{y,sw}$ and W_{py} parameters was carried out by the authors of this article with the use of a physical model of reinforced earth massif (Fig. 2) and presented, inter alia, at the XVI Franco-Polish Colloquium Forum in Montpellier, 2013 [19].

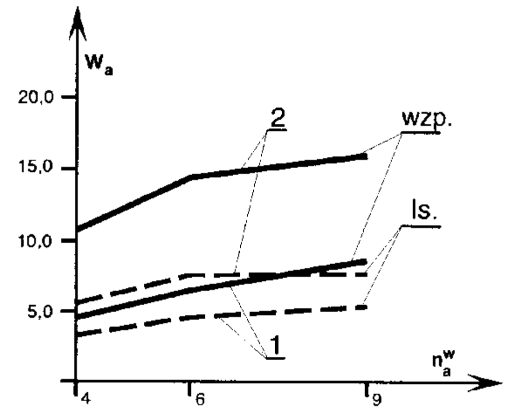

Fig. 4. General coefficient of cooperation W_a system ground-reinforcement [20]: n_a^w - number of inserts in the layer (according to reinforcement systems A, B, C), 1 - reinforcement insert with notches, 2 - inserts without notches, --- ground mass loosely poured (*l.s.*), --- ground pre-compacted surface mass (*w.z.p.*)

Table 3. General indicator of cooperation of the ground material system - reinforcement inserts W_a [20]: *b.k.* - inserts without notches, *k* - inserts with notches, 9, 6, 4 - number of inserts in a single reinforcement layer (according to systems A, B, C)

W_a	Loose sand Number of inserts in a layer					
	9		6		4	
	b. k.	k.	b. k.	k.	b. k.	k.
	8,20	5,83	7,61	4,86	5,83	3,43
W_a	Surface precompacted sand Number of inserts in a layer					
	9		6		4	
	b. k.	k.	b. k.	k.	b. k.	k.
	16,23	8,89	14,63	7,11	11,06	5,03

Fig. 5 and Table 4 show the variability of the coefficient of cooperation (calculated from formula 9) in the individual five reinforcement layers (located on the measurement levels of the model z_1, z_2, z_3, z_4, z_5- fig. 2), in the case of the model with the reinforcement according to the system A (9 inserts in each layer). The values of the reinforcement co-operation indicator with the ground centre depend on the physical features of the soil (including density), the amount of reinforcement (the density of the inserts) and the mechanical quality of the insert surface (determining the frictional dimension on the contact with the ground centre). The improvement of cooperation efficiency is influenced by the installation of appropriate retaining elements on the surface of the tapes. The quality of the analyzed cooperation is not the same at the height of the massif. The best reinforcement effects are obtained in the upper zone of the physical mass model under investigation.

Comparing the indexes for loose sand and pre-compacted sand mass, it was found that the quality of reinforcement with soil is definitely lower in the massif of pre-compacted sand, reinforced with inserts without notches - then there is significant slip of ground grains on the surface of the inserts.

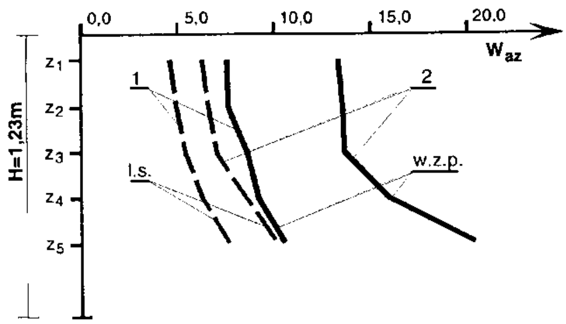

Fig. 5. Cooperation coefficient $w_{a,z}$, with in particular five reinforcement layers, for the model with reinforcement according to system A [20]: z_1, z_2, z_3, z_4, z_5 - measuring levels of the retaining wall of the model, H - height of the model, 1 - inserts with notches, 2 - without notches, --- ground mass loosely poured (*l.s.*), -- - pre-compacted surfaced (*w.z.p.*)

Table 4. Indicator of cooperation on the contact of the ground centre with the reinforcement of W_a, z in each of the five layers of reinforcement of the massif model. Laboratory tested case installing nine inserts in each horizontal reinforcement layer [20]: *b.k.* - inserts without notches, *k.* - notches with notches

Depth in the massif z_k [m]	$w_{a,z}$ Indicator			
	the soil loosely poured		pre-compacted soil surfactant	
	b.k.	***k.***	***b.k.***	***k.***
z_1 = 0.095	6.25	4.68	13.32	7.61
z_2 = 0.290	6.56	4.95	13.33	7.46
z_3 = 0.485	6.40	5.36	12.04	8.48
z_4 = 0.680	8.47	6.25	15.54	9.10
z_5 = 0.875	10.09	7.50	19.64	10.37

5. Summary

The basis for introducing the concept of "cooperation index" (characterizing the quality of the engineering structure construction with reinforced soil) and estimating its value are experimental investigations of deformations (essentially horizontal) of the physical model of a reinforced earth with a vertical wall [20]. Deformation of the massif was generated using a static vertical pressure in the plane of the ceiling of the model with a maximum value of q = 61.69 kPa. The effect of the mentioned research was the estimation of the wedge of the fracture in the limit state of the active pressure of the soil material on the retaining (measuring) wall of the massif model.

According to the accepted condition concerning the work of reinforcement without slip, it was assumed that the reinforcement should take over the entire horizontal force originating from the wedge pressure of unreinforced soil. The wedge pressure was separated into individual reinforcement layers and the number of inserts needed was calculated. Model tests have shown (Table 1) that the reinforcement in practice works with slipping. In addition, the demand for inserts results from the course of the pressure graph from the wedge of the wedge [20], i.e. it is not the same at the height of the massif (Table 2) - in design practice, the same number of inserts is received in each horizontal reinforcement layer.

The quality of reinforcement cooperation with the soil is expressed by the so-called cooperation indicator. The value of the indicator depends mainly on the condition of soil compaction, the amount of reinforcement and the technical quality of the insert surface (characterized by the coefficient of friction on contact with grains of soil material). The most favourable cooperation was found in the case of the minimum amount of reinforcement (used in model tests) containing surface retaining elements. The quality of cooperation is not the same at the height of the massif - the best effects of reinforcement were obtained in the upper zone of the physical mass model under study.

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