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Effectiveness of road embankment reinforcement in the light of model tests on a laboratory scale

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Abstract
The subject of the article concerns road embankments made of reinforced soil. The results of the analysis of the effectiveness of the reinforcement of these structures as a function of selected variable factors concerning the soil medium and the parameters of reinforcement inserts are given. The efficiency analysis was carried out on the basis of measurements of the horizontal unit pressure made on a physical model of a soil massif with a vertical wall of reinforced soil. The large-scale model was constructed on a laboratory scale. The article ends with a summary containing conclusions of a cognitive and practical nature.

Keywords: road embankments, reinforced soil, efficiency, model tests

1. INTRODUCTORY REMARKS AND RESEARCH PURPOSE

A laboratory model of a road embankment with a vertical wall, made of reinforced soil according to the classic technology developed by H. Vidal (Fig. 1) [1 ÷ 3, 7, 14, 15] is being considered. Objects of this type have been used quite widely in the world for several decades, especially in specific cases, e.g. reconstruction or reconstruction of damaged engineering structures (e.g. embankments on access roads to bridges - Fig. 2 [3], bridge abutments - Fig. 3 [6], fig. 4 [3]). In recent years, the number of these facilities in Poland has been dynamically increasing, implemented along the lines of modernized national expressways [18 ÷ 22]. Among national research centres conducting experimental research in the field of reinforced soil technology, the Institute of Hydroengineering of the Polish Academy of Sciences in Gdańsk deserves special attention [4, 5, 8 ÷ 13]. The achievements of this centre include: theoretical and experimental analyses of the functioning of reinforced soil structures (based on theoretical and physical laboratory models and a large-scale model of a geosynthetics reinforced soil retaining wall), expertise and own projects completed with implementations [4].

This article presents the results of horizontal pressure tests in the soil medium, carried out on a large-scale laboratory model of a reinforced soil retaining structure. The ground massif was loaded with static vertical pressure simulating the operational load of road vehicles.

The aim of the research was to identify the phenomenon of the active pressure of non-cohesive soil on the vertical retaining wall of the model as a function of variable factors: operational load value, type of reinforcement inserts and the state of compaction of the soil medium.

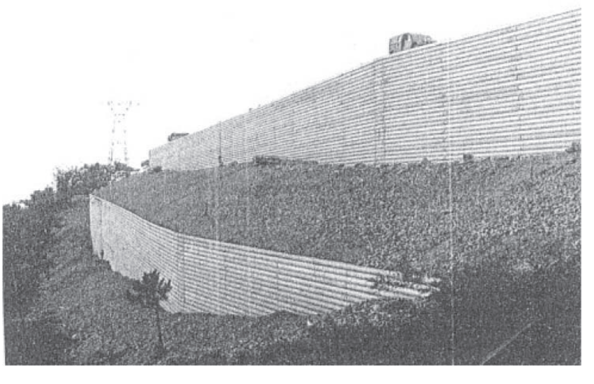

Fig. 1. Vertical reinforced soil walls in the Vigna road embankment (France). View of the massif casing [14]

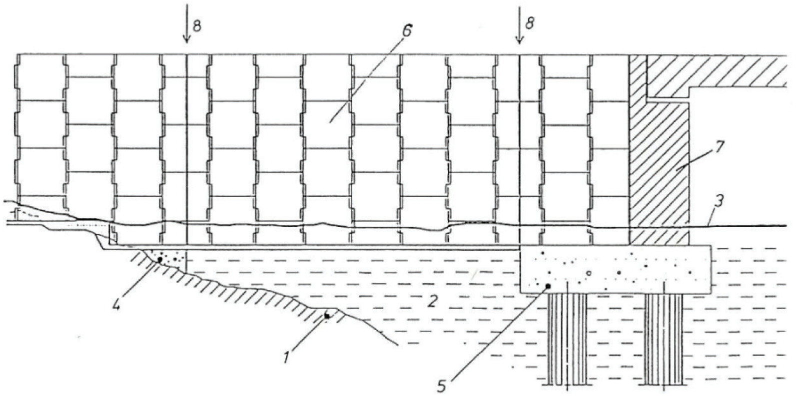

Fig. 2. Abutment of the bridge on weak soils, with an access road constructed of reinforced soil [3]:
1 - rocky subsoil, 2 - compressible (weak) soils, 3 - ground surface, 4 - concrete „seal" replacing a block of weak soil, 5 - pile cap of the foundation, 6 - reinforced soil structure as access to the abutment, 7 - abutment body, 8 – dilatation

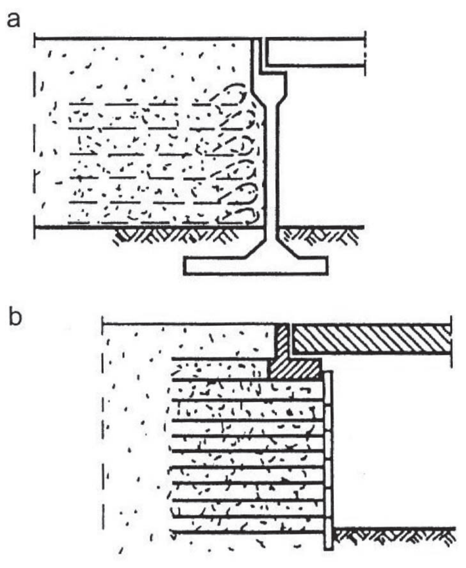

Fig. 3. An example of a bridge abutment [6]: a - reinforced with geosynthetics, b - made of reinforced soil

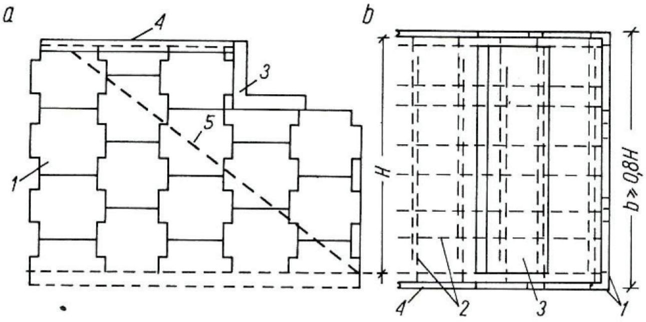

Fig. 4. Reinforced soil abutment in a road bridge [3]:
a - vertical longitudinal view,
b - top view,
1 - curtain wall made of modular concrete prefabricates,
2 - reinforcing strands backfill of the abutment,
3 - bed footing,
4 - prefabricated cornice beam,
5 – contour the embankment cone

The effectiveness of the reinforcement was estimated, which was determined by the index expressing the ratio of the horizontal pressure P_y^* in the reinforced soil model to the horizontal pressure P_y in the soil medium model without reinforcement, treated as a model.

2. RESEARCH STAND AND METHOD

The test stand is a steel, rectangular container (Fig. 5) [16, 17]. Measurements of the horizontal pressure in the soil medium on the vertical retaining wall (1) of a special structure enabling the elastic-plastic movement of this medium were carried out. Permanent contact with the pressing ground is ensured in all phases of the experiment. The earth pressure (in the range from „at rest" to the active boundary) initiating the horizontal displacements of the measuring elements (3) of the retaining wall was induced by a special, vertical static load, using a rectangular, rigid steel plate - also called a punch, due to its characteristic shape (2). The slab loading the ground massif was positioned horizontally, transversely to the model retaining wall, at a distance of l_y = 0.30 m from this wall. The unit load is 0.0 ÷ 61.69 kPa and meets the conditions:

- it is minimal, but necessary to create the boundary state of active pressure in the soil medium,

- only the local displacement of the soil medium from under the punch is allowed, without affecting the readings of pressure sensors in the retaining wall.

The bulk material is coarse, different-grained sand, characterized by the heterogeneity index $U = 12$ and humidity at the level of 0.3%. The research tests were carried out in two states of soil compaction: loosely filled and pre-compacted. Reinforcement inserts were used in the form of two kinds of flaccid steel strips (coated with a thin layer of polyethylene insulation): with a smooth surface or with a surface profiled with special „notches". The „notches", i.e. the retaining elements profiling the surface of the insert, were special sections with an angular cross-section, attached (in the technology of electric resistance welding) to the surface of the reinforcement strips (Fig. 6). The inserts were placed in horizontal layers with a vertical distance $e_z = 0.195$ m.

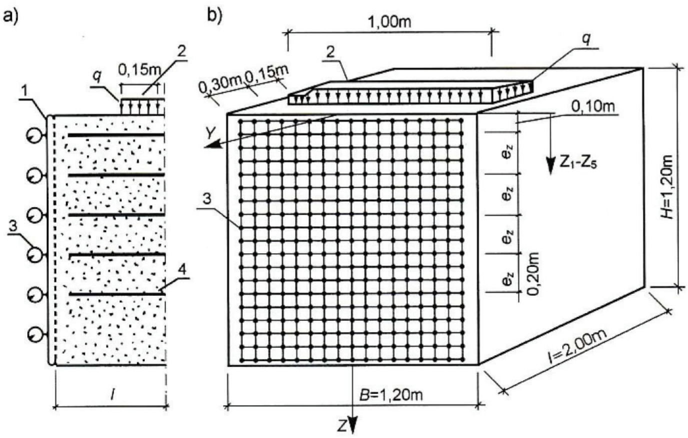

Fig. 5. Scheme of the test stand (model of a massif supported by a reinforced soil wall) [16, 17]:

a - fragment of the longitudinal vertical section, *b* - general view, *1* - measuring retaining wall,

2 - 0.15x1.0 m plate generating the test load, *3* - horizontal displacement sensors,

4 - reinforcement inserts, z_1-z_6 - measurement levels for ground massif displacements

The following configurations of the soil mass model reinforcement were introduced (Fig. 7, 8):

A - 5 layers of 9 inserts (in the form of tapes) in a layer (45 inserts in total), insert length l_a = 1.80 m, horizontal distance e_x = 0.11 m;
B - 5 layers of 6 tape inserts (30 inserts in total), insert length l_a = 1.80 m, horizontal distance e_x = 0.17 m;
C - 5 layers of 4 tape inserts (20 inserts in total), insert length l_a = 1.80 m, horizontal distance e_x = 0.23 m,
D, E and F - with tape inserts with the following lengths: 1.80 m (D), 1.30 m (E) and 1.00 m (F), arranged on the two upper measurement levels (z_1 and z_2) after 9 pieces on each level (18 inserts in total) at a horizontal distance of e_x = 0.11 m,
G - with reinforcement at the levels z_1 and z_2, in the form of grates l_a = 1.80 m long. The grates are made of tapes crossed perpendicularly and stiffened at the nodes. The dimension of the square mesh of the grate in the belt axes is $e_x = e_y$ = 0.11 m.

Configurations A, B, and C use plain or „notched" tape, other configurations only use no notches.

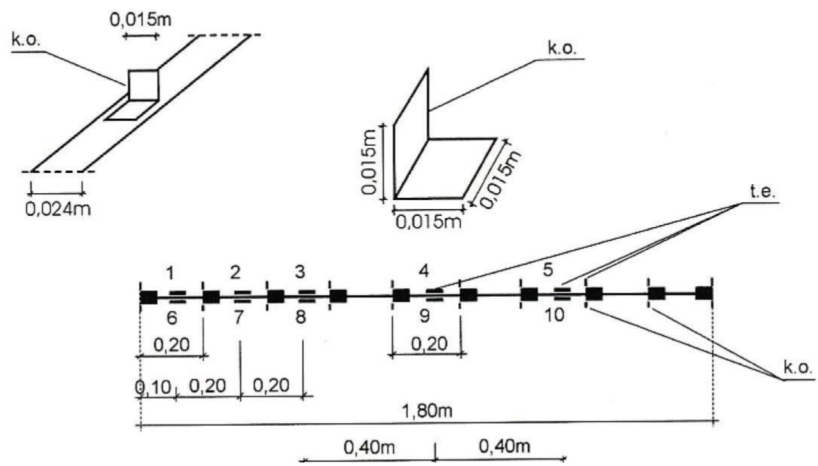

Fig. 6. Reinforcement strip with notches (stop angles) [16, 17]:
k.o. - stop angle,
t.e. - electrofusion strain gauges glued on the upper surface (No. 1 ÷ 5) and the lower surface (No. 6 ÷ 10)

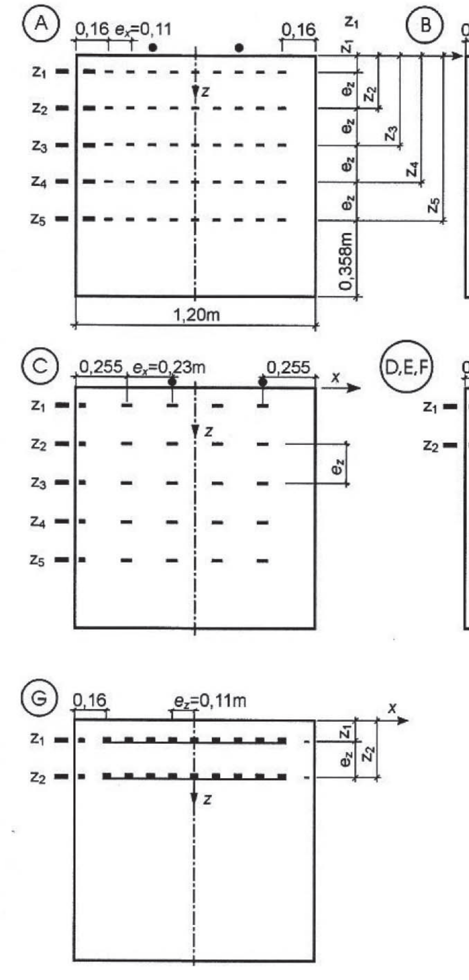

Fig. 7. Vertical cross-section through the massif model with the arrangement of reinforcement inserts [16, 17]:
A, B, C, D, E, F - tape reinforcement configurations;
G - model with lattice reinforcement;
z_1 = 0.095 m;
z_2 = 0.290 m;
z_3 = 0.485 m;
z_4 = 0.680 m;
z_5 = 0.875 m - levels on which the reinforcement layers are located

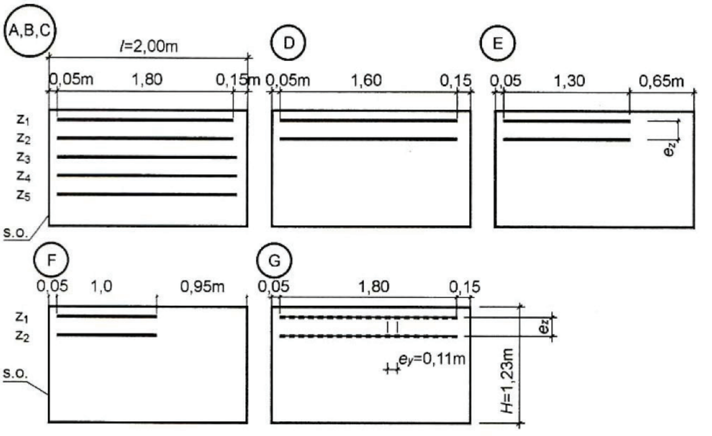

Fig. 8. Vertical longitudinal section through the massif model, with a view of the reinforcement inserts [16, 17]:
A, B, C, D, E, F - tape reinforcement configurations;
G - model with lattice reinforcement, *s.o.* - model retaining wall with horizontal displacement sensors

On the surface of the reinforcement strips, electrofusion strain gauges are glued on both sides in order to monitor the deformation. Diagnosing the state of deformation of the reinforcement inserts was the basis for determining the values of normal (tensile and compressive) and tangential stresses, and ultimately - to estimate the size of a solid soil fragment in the limit state of active pressure.

3. THE RESEARCH RESULTS

3.1 Horizontal pressure of the soil mass as a function of the external load

Fig. 9 illustrates the graphs of the unit distribution of the horizontal pressure of a soil mass (coarse mixed sand) of unreinforced, loosely packed and (alternatively) pre-compacted soil, in various states of external load.

Figures 10, 11 and 12 show the course of the unit horizontal pressure in the reinforced massif. Graphs of the average horizontal pressure of the soil mass as a function of the height of the external load are presented in Figure 13. The average horizontal pressure of the soil on the retaining wall of the model was determined as follows:

$$p_{y,śr} = 1/6 \sum p_{y,k} \qquad (1)$$

where:
k = 1, 2, 3, 4, 5, 6 - successive measurement levels of the model retaining wall,
$p_{y,k}$ - unitary horizontal pressure of the soil mass at a given measurement level [kPa].

The values of the massif pressure $p_{y,śr}$ in the case of a load condition $q = 0$ are generated by the self-weight of the soil mass, which is measured by the vertical stress calculated according to the formula:

$$\sigma_z = \gamma_0 \cdot z \qquad (2)$$

where:
γ_0 - volumetric weight of the soil medium forming the massif which is the subject of the research,
z - level in the massif at which the weight of the „overburden" of soil is calculated [m].

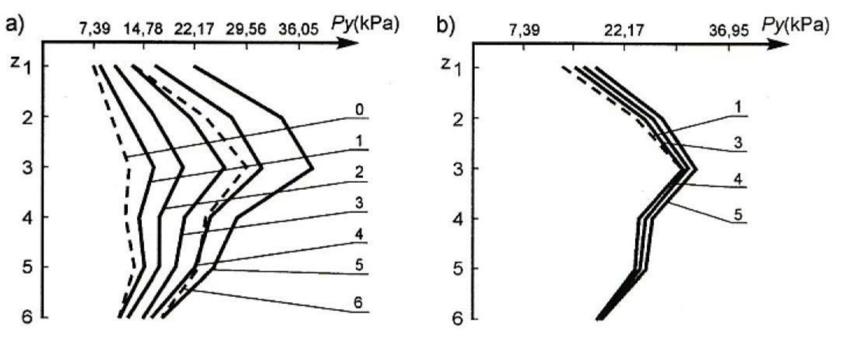

Fig. 9. Graphs of the unit horizontal pressure in the unreinforced soil mass as a function of the increasing external load [17]:
a - loosely covered soil (sand),
b - pre-compacted,
0 - without external load,
1 - load with the value q = 12,34 kPa,
2 – q = 24, 68 kPa,
3 - q = 37.02 kPa,
4 - q = 49.36 kPa,
5 - q = 61.69 kPa,
6 - state after complete load removal

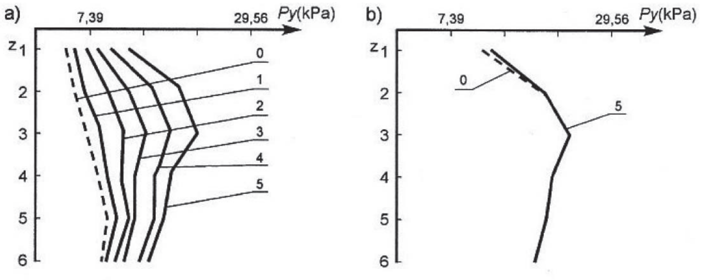

Fig. 10. Graphs of the unit horizontal pressure in the soil mass with unnotched tapes reinforcement (configuration A), as a function of increasing external load [17]:
a - loosely poured,
b - pre-compacted,
0 - no external load,
1 - load o values of q = 12.34 kPa,
2 - q = 24.68 kPa,
3 - q = 37.02 kPa,
4 - q = 49.36 kPa,
5 - q = 61.69 kPa

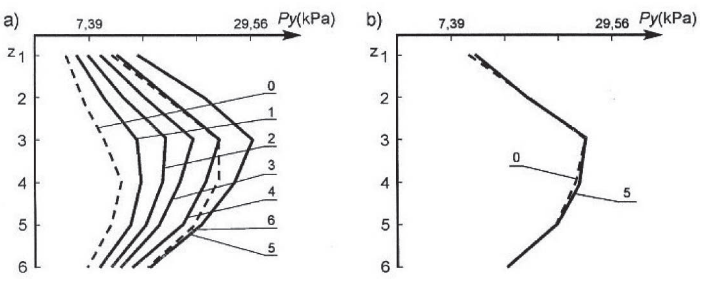

Fig. 11. Graphs of unitary horizontal pressure in soil mass with unnotched tapes reinforcement (configuration D), as a function of increasing external load [17]:
a - loosely poured,
b - pre-compacted,
0 - no external load,
1 - load o values of q = 12.34 kPa,
2 - q = 24.68 kPa,
3 - q = 37.02 kPa,
4 - q = 49.36 kPa,
5 - q = 61.69 kPa,
6 - state after complete load removal

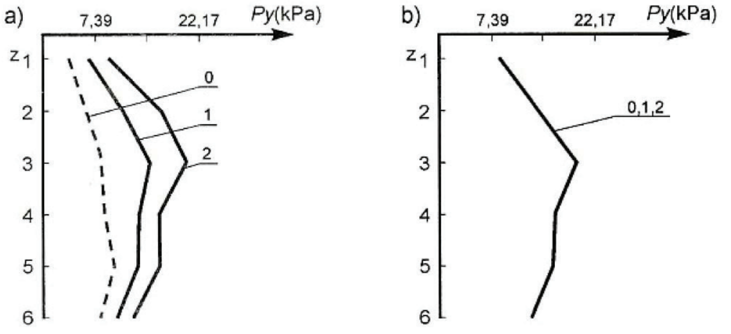

Fig. 12. Graphs of the unit horizontal pressure in the soil mass with notched strips reinforcement (configuration A), as a function of increasing external load [17]:
a - loosely poured,
b - pre-compacted, 0 - no external load, 1 - load q = 37.02 kPa, 2 - q = 61.69 kPa

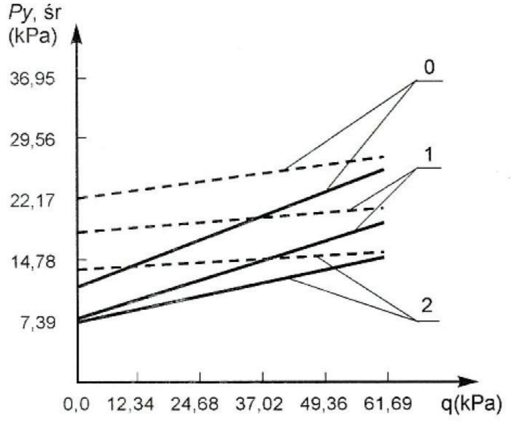

Fig. 13. Graphs of average horizontal pressures of the soil mass $p_{y,śr}$ as a function of the external load q [17]:
---- loose soil massif (sand),
- - - pre-compacted massif,
0 - without reinforcement (pattern),
1 - reinforced with tapes without notches (configuration A),
2 - reinforced with tapes with notches (configuration A)

In terms of the applied external vertical load on the massif ceiling in the discussed studies, the diagrams of horizontal soil pressures on the retaining wall, presented as a function of individual stages of the height of this load, show a linear relationship of the form: $y = ux + v$. The dimension of the slope of the straight lines to the abscissa (Fig. 13) can be interpreted as a measure of „expansion" properties (characterizing the range of horizontal deformations) of a given model of a reinforced soil massif. These properties can generally be defined by the experimental horizontal pressure coefficient K_d. The value of this coefficient is related to the test conditions for the deformation state of the physical models of the soil massif and is as follows [16, 17]:

$$K_d = \Delta p_y \cdot (\Delta q)^{-1} \tag{3}$$

where:
Δp_y - increase of the unit horizontal pressure [kPa],
Δq - increase in unit vertical load [kPa].

The values of the K_d coefficient in the case of the reinforcement configuration A are given in Table 1. The K_d parameter shows lower values for the soil with the reinforcement and decreases with the increase of the effectiveness of the reinforcement in the soil medium. A similar relationship can be shown in the case of other reinforcement configurations. The horizontal pressure coefficient in reinforced soil, marked as K^*, can be generally expressed by the formula [16]:

$$K^* = K - \Delta K, \quad 0 \leq \Delta K < K \tag{4}$$

wherein:
K - soil pressure coefficient without reinforcement,
ΔK - reduction value of the pressure coefficient generated by the influence of reinforcement inserts.

Appropriate research tests, carried out on the physical models of reinforced soil (concerning the three-dimensional state of stresses and deformations), and then the synthetic analysis of the results, made it possible to include the value of the reduction of the pressure coefficient using the experimental formula [16, 17]:

$$\Delta K = K - K^{*} = (\text{tg } \varphi)^{-1} \cdot E \cdot \mu_{c} \cdot W \tag{5}$$

where:

φ - angle of internal friction, determining the state of soil compaction, product ($E \cdot \mu_c$) - generalized reinforcement parameter characterizing the strength properties of reinforcement inserts and their number,

E - modulus of elasticity of the reinforcement material [kN / m2],

μ_c - percentage of reinforcement [%], expressing the amount of reinforcement in the cross-section of a reinforced soil model,

W - correction factor for the technical specificity of research tests.

Tab. 1. Angular coefficients K_d of the $p_{y,śr}$ function with an external load q = 61.69 kPa generated in the plane of the top of the soil massif model q = 61.69 kPa [17]

Type of experience		*Kd* coefficient	
		Loosely poured soil	Surface pre-compated soil
Not reinforced sand		0.39	0.14
Reinforced sand	Smooth tapes (A type of reinforcement)	0.32	0.07
	Tapes with notches (A type of reinforcement)	0.21	0.05

3.2 *Effect of one-way reinforcement on the reduction of horizontal soil pressure*

The effect of the number of reinforcement inserts on the reduction of horizontal soil pressure (sand) was expressed by the W_p index, calculated according to the quotient of the total horizontal soil pressure (sand) with reinforcement P_y^* to the value of horizontal sand pressure without reinforcement P_y. The W_p index means the reduction of the horizontal pressure of the sand mass on the retaining measuring wall (due to reinforcement), in a percentage ratio:

$$W_p = [100 - P_y^{*} \cdot (P_y)^{-1} \cdot 100], \quad \% \tag{6}$$

In the above dependency P_y means the total horizontal pressure of the sand massif against the surface of the retaining wall. The P_y parameter for unreinforced sand

and P_y^* for reinforced sand were calculated as the area of the unit pressure diagrams $p_y = f(z)$ at the wall height of the model H = 1.20 m:

$$P_y = \int p_y\,(z)\,dz, \quad z = 0 \div H \qquad (7)$$

Table 2 and Figure 14 show the values of the W_p index, which characterizes the effect of one-way reinforcement (tape-shaped inserts) on the reduction of horizontal soil pressure. This influence is presented depending on: the type of reinforcement (strip without notches or with notches), configuration of the inserts (reinforcement distribution), the number of inserts and the amount of external load. The value of the W_p index increases with the increase of the load (used in the discussed research tests) generated on the roof of the massif model made of reinforced soil. Reinforcement, as a passive element, cooperates with the soil medium under the influence of the transferred forces on the contact surface. Therefore, it is economical to locate the reinforcement inserts in the zones of occurrence of significant loads of the soil medium, which, as tangential and normal forces to the surface of the inserts, cause stretching of the reinforcement material. Table 2 and Figure 14 also show that in sand reinforced with notched tapes, the effects of the reinforcement consisting in reducing the horizontal pressure practically do not depend on the change in soil compaction (within the scope adopted in the research tests). In non-notched strip-reinforced sand subjected to initial compaction load, the effects of the reinforcement decrease by an average of about 30%. In the case of using such inserts, it is advisable to reinforce poorly compacted soils.

Tab. 2. W_p indicator for the reduction of the horizontal pressure of the sand mass on the retaining wall of the model (reinforcement according to configuration A, B and C) [17]

Type of reinforcement	Method of reinforcement	Number of reinforcement inserts na (pieces)	Punch load q [kPa]			
			37.02		61.69	
			W_{p_y} [%] coefficient [%]			
			l.p.s.*	s.p.s.**	l.p.s.*	s.p.s.**
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

* - loosely poured soil
** - surface pre-compacted soil

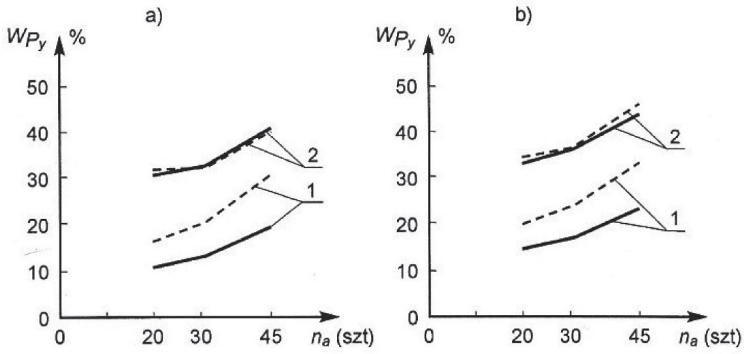

Fig. 14. W_p indicator of the reduction of the horizontal pressure of the sand mass on the retaining wall of the model, as a function of the amount of reinforcement measured with the parameter n_a = 20, 30, 45 pieces of inserts [17]:
a - load condition q = 37.02 kPa,
b - q = 61.69 kPa,
- - loose soil mass (sand),
- - - pre-compacted mass,
1 - not notched strips (configuration A),
2 - notched strips (configuration A)

As you know, the cooperation of the reinforcement inserts with the soil medium takes place on the basis of friction (the size of which depends on the shape of the inserts' surface). When using reinforcement inserts in the form of grids or meshes, there is an additional resistance to the transverse movement during deformation of the loaded layer of reinforced soil.

Considering the interaction of the notched inserts with the pre-compacted soil, the possibility of significant slippage is noticed. The slip phenomenon can be reduced or completely eliminated by installing appropriate resistance elements on the flat surfaces of the inserts. In this way, an increase in the efficiency of the insert in the soil medium is obtained. The conclusion is that notched inserts can be used correspondingly less than the same ones with a smooth surface, in order to obtain the designed reduction of the horizontal earth pressure (Fig. 14). Figure 14 shows that, assuming a reduction of soil pressure, e.g. at the level of W_p = 30%, in the tested massif model, the wear of the reinforcement tapes with a smooth surface is more than twice as high as the wear of tapes with notches installed on both sides.

3.3 *Effect of the length of one-way reinforcement inserts on the change of horizontal soil pressure*

The research tests were performed assuming a constant number of reinforcement inserts in the vertical cross-section of the soil massif model: n_a = 18 tapes. Figure 15 compares the pressure diagrams of reinforced sand in configurations D, E and F. The influence of the reinforcement located only in the two upper measurement levels of the model z_1 and z_2 on the change in the nature of the horizontal pressure diagram covers a vertical zone with a range of about 0.55 *H* from the upper edge of the retaining wall (*H* is the height of the wall). This is called the zone of interaction of the reinforcement with the soil centre. The graphs (Fig. 15) show that the range of this zone does not change in the case of changing the length of the inserts (within the range adopted in the research tests). The course of the graphs in Figure 15 can be justified by the length of the inserts used. Inserts with lengths l_a = 1.00 m; 1.30 m and 1.80 m completely cover the range of the so-called the fracture wedge in the limit state of active earth pressure. On the other hand, changes in the length of the inserts contributed to slight fluctuations in the W_p reinforcement efficiency index (Table 3). Regarding the so-called the fracture wedge, it should be emphasized that the authors performed model tests, as a result of which the horizontal range of the fraction body L_y was estimated on the massif ceiling (in an identical sand massif model), with the value L_y = 1.05 m in the case of the loose massif and L_y = 0, 90 m for a pre-compacted massif.

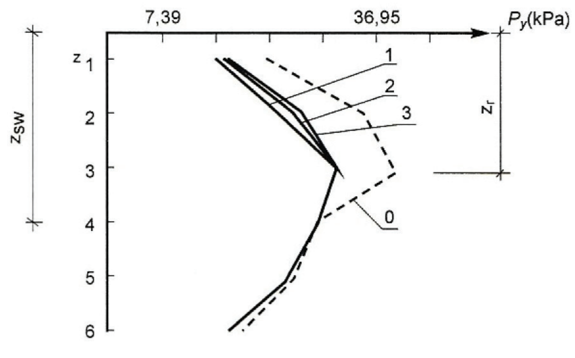

Fig. 15. Diagrams of the horizontal pressure (on the retaining wall) of a loose sand massif, as a function of the length of the reinforcement inserts, located on the two upper measurement levels of models z_1 and z_2 [17]. External load q = 61.69 kPa,
0 - sand massif without reinforcement (pattern),
1 - reinforced according to configuration D (length of inserts l_a = 1.80 m),

2 - according to configuration E (l_a = 1.30 m), 3 - according to F (l_a = 1.00 m), z_{sw} - vertical range of changes in the course of the pressure diagram as a result of installing the reinforcement, z_r - vertical range of changes in the course of the pressure diagram due to changes in the length of the inserts

Tab. 3. Index of reduction of the horizontal earth pressure on the retaining wall of the W_p massif model as a result of reinforcement according to the configuration D, E, F and G. Data refer to the loosely covered massif [17]

Type of reinforcement	Method of reinforcement	Total reinforcement n_a (pieces)	W_{Py} coefficient [%]
Tapes without notches	D E F	18 18 18	17.39 13.59 11.85
Two-way reinforcement (lattice)	G	2	25.87

3.4 Influence of two-way reinforcement on the change of horizontal soil pressure

Two-way reinforcement in the form of gratings was introduced for comparative purposes. It shows the main advantage in relation to one-way reinforcement - increased resistance to pulling out from the soil medium, resulting from additional forces acting perpendicular to the longitudinal axis of the inserts. Fig. 16 shows the graphs of the unit horizontal pressure of a sand mass, loosely covered, loaded with a unit pressure of q = 61.69 kPa, reinforced with tapes in a one-way manner, according to configuration D (1) and configuration A (2) and with two-way gratings according to configuration G (3). In each case, the reinforcement has the same length l_a = 1.80 m. The reinforcement efficiency index W_p in the case of the lattice reinforcement (configuration G) is given in Table 3.

The vertical range z_{sw} of the impact of two-way reinforcement, i.e. with two gratings located at the measurement levels z_1 and z_2 (curve 3), covers 0.55 H (H is the height of the retaining measurement wall), measured from the upper edge, i.e. the same as in the case of two layers of one-way reinforcement, located at the same levels z_1 and z_2 (curve 1).

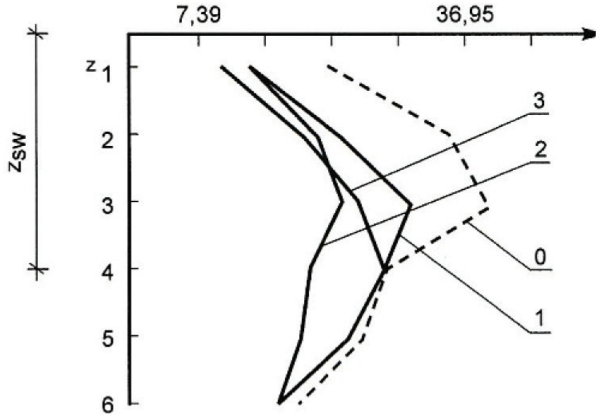

Fig. 16. Diagrams of the horizontal pressure of loose sand, reinforced with non-notched inserts [17]:
external load condition q = 61.69 kPa,
0 - unreinforced (pattern),
1 – one-way reinforced acc. to D configuration,
2 – one-way reinforced acc. to A configuration,
3 – two-way reinforced according to configuration of G

However, the reduction of the horizontal pressure due to two-way reinforcement (in configuration G) in relation to one-way reinforcement (longitudinally with two layers of tapes - configuration D) has a larger dimension and amounts to (Table 3): $W_p^G - W_p^D = 25.87 - 17.39 = 8.48\%$. On the other hand, the reduction of pressure as a result of bidirectional reinforcement (in configuration G) is smaller compared to the reinforcement according to configuration A (45 strips without notches) by the following value (tables 2 and 3): $W_p^A - W_p^G = 32.60 - 25.87 = 6.73\%$.

4. CONCLUSIONS

- The dependence of the value of the horizontal soil pressure on the vertical load on the soil mass used in the research tests shows a linear course in the loosely filled and pre-compacted soil medium (general conclusion).
- The soil pressure on the retaining wall of the tested model, generated as a result of the external load on the top of the pre-compacted massif, without reinforcement or reinforced, was obtained in each analysed case with a value

lower than for the loosely filled soil. Thus, the relationship between the value of horizontal pressure in a non-cohesive, non-reinforced or reinforced soil medium and the change in the value of the angle of internal friction was confirmed.

- Horizontal pressures of sand massif with reinforcement (regardless of the state of compaction) and vertical displacements (settling) of the strip loading the ceiling of the modelled massif, in each tested case are lower than in the case of an unreinforced massif and depend on the amount and type of reinforcement (inserts without notches or with notches).
- The proportionality of the settlement of the punch loading the roof of the modelled massif, in relation to the size of this load, depends on the compaction of the soil medium, the amount and type of reinforcement, and is indirectly related to the distance of the loading band (punch) from the plane of the retaining wall of the model. The proportionality range is greater for pre-compacted sand. Moreover, in the course of the conducted research tests, the basic principles of soil mechanics were confirmed, which proves the correctness of the adopted research method.

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