10.26411/83-1734-2015-1-53-6-22

Electrofusion Tensometry Applied to the Research of Engineering Structures

Zenon Zamiar
The International University of Logistics and Transport in Wrocław, Poland

Andrzej Surowiecki
General Tadeusz Kościuszko Military University of Land Forces in Wrocław, Poland

Abstract
The subject of the article concerns the problem of estimating the location of a slip line in a massif with a vertical retaining wall made of reinforced soil, in which the limit state of active pressure was induced. The task is solved experimentally, on the basis of measured unit strains in the reinforcement inserts, with the use of electrofusion strain gauges. The inserts are located in horizontal layers. The slip curve is formed by the points where the maximum normal stresses occur in the reinforcement inserts. This curve cuts off the fragment wedge that is being sought from the plane of the retaining wall. The slip line divides the area of the massif into two zones: active (splinter wedge) and passive, in which the reinforcement inserts are anchored.

The test stand is presented, the technique of measuring the deformation of the reinforcement and the method of estimating the location of the slip surface are discussed.

Keywords: reinforced soil, retaining structure, splinter wedge, electrofusion strain gauge

1. OBJECT, RESEARCH METHOD AND TEST STAND

The object of research is a physical model of the massif with a vertical wall made of reinforced soil, made on a laboratory scale. The model is placed in a rectangular container, the diagram of which is shown in Fig. 1 [14, 15]. The structure of one of the front walls (the so-called measurement wall) enables the measurement of horizontal displacements of the soil mass, which is a measure of the active pressure. In the boundary state of active ground pressure, a slip line is formed, separating the fragment of the fragment (the so-called wedge) from the remaining (stationary) part of the soil massif. The fracture wedge is a factor that generates the soil pressure on the plane of the retaining (measuring) wall.

The soil material filling the test container is dry coarse-grained sand, characterized by physical parameters [14, 15]: volumetric weight in the loosely covered state $\gamma_0 = 19{,}0$ kN/m^3, natural humidity in $w_n = 0{,}3\%$, degree of compaction in the loosely covered state $I_D = 0.38$ and the angle of internal friction $\phi = 30{,}2^0$ (determined for a sand sample in a laboratory direct shear apparatus).

Reinforcement inserts were used in the form of "flaccid" tapes with a length of $l_a = 1.80$ m and a cross-section of b_a x $g_a = 0.024$ m x 0.001 m (b_a - width, g_a - thickness) [14, 15]. The inserts, made of hardened spring steel with the symbol 50HSA (characterized by a modulus of longitudinal elasticity $E = 210{,}437.7$ MPa), are arranged in five horizontal layers. The vertical spacing of the individual reinforcement layers is $e_z = 0.195$ m. In each layer, 9 tapes are located parallel to the longitudinal axis of the container, with the same horizontal axial spacing $e_x = 0.11$ m. Thus, the total number of inserts in the model is $n_{a,c} = 45$ pieces.

Special "notches" in the form of steel angles were attached to the surface of the reinforcing tapes of the modeled soil mass on both sides (by electric welding) (Fig. 2). These angles, spatially shaping the surface of the tapes, increase the resistance of the inserts to displacement in the soil medium.

One of the intermediate stages of the research was the determination of normal stresses in the reinforcement inserts by means of strain gauge measurements of unit strains. Therefore, the use of "flaccid" inserts guaranteed the initiation of measurable deformations. The location of the strain gauges along the strips is designed in such a way as to cover mainly the active zone (i.e. the range of the splinter wedge) and partially the anchoring zone. The strain gauges are coated with resin, protecting them against mechanical damage and moisture. Measurements and registration of strain gauge indications were carried out using a multi-point, automatic set for deformation tests, consisting of a set of devices: an automatic strain gauge bridge, a module controlling the measurement and connection of strain gauges, strain gauge boxes and a microcomputer with a printer.

The main aim of the research was to estimate the position of the slip line (assuming a two-dimensional model system) in the limit state of active pressure in the soil mass. The slip line was obtained as the geometric location of the maximum normal tensile stresses in the inserts, located on the individual five measurement levels of the model. The stress values were expressed by the classical Hooke's relationship $\sigma = E\ \varepsilon$.

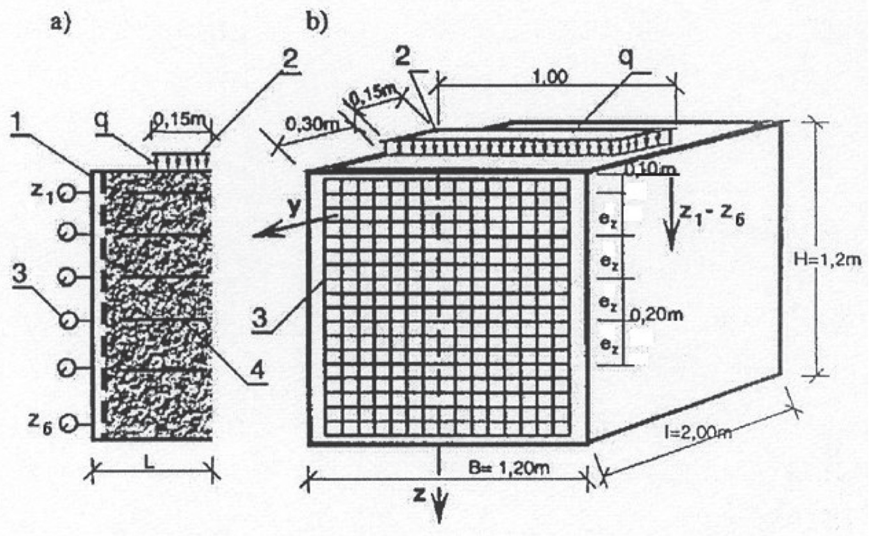

Fig. 1. Diagram of the test stand [14, 15]:
a - fragment of the vertical section,
b - general view,
1 - model retaining (measuring) wall,
2 - loading plate with dimensions of 0.15 x 1.0 m;
3 - horizontal displacement sensors,
4 - reinforcement inserts; z1, z2, z3, z4, z5, z6 - measurement levels

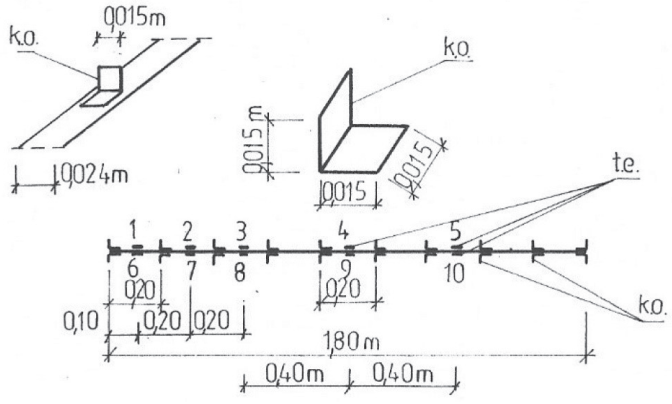

Fig. 2. Reinforcement inserts with retaining elements in the form of angles [14, 15]: t.e. - electrofusion strain gauges installed on the surface of the insert (1-5) and lower (6-10), k.o. - stop angles

As it is known, in the field of experimental research and theoretical analyzes, the subject matter is well understood [1-13, 16]. However, the developed (as a result of advanced research and analysis) foundations for the functioning of reinforced soil as a material forming engineering structures are in many cases based on simplifying assumptions. Therefore, it is justified to conduct experimental studies in which the dependencies between the parameters characterizing the process of cooperation of the soil medium (which is the matrix) with the reinforcement inserts are determined by direct measurement. Therefore, this article presents an approach based on analyzing the functioning of reinforced soil on the basis of research tests performed on physical models on a laboratory scale. The adopted laboratory method of research allows for maintaining the relative specificity of the experimental conditions and for a programmed change of one of the parameters sought, while maintaining the invariability of the others [15].

The designed vertical load on the soil massif model results from the research method and is mainly the factor initiating the generation of the fragmentation solid. They should be treated as approximate, but within acceptable limits. The load was carried out in a static manner, through a steel plate with dimensions of 0.15 x 1.0 m located horizontally, transversely to the longitudinal axis of the model. The minimum distance of the slab edge from the inner face of the end wall was taken as l_y = 0.30 m. The load value (in the range of 0-61.69 kPa) was used the same for all tests and minimal but necessary to produce a fragment of the fragment in the soil massif model.

Two states of compaction of the soil massif were realized: loosely filled (l.f.) and surface pre-compacted (s.p-c.). The measurement of deformations in the reinforcement strips was performed consecutively for two load conditions of the top of the soil massif: q = 37.02 kPa and qmaximum = 61.69 kPa.

2. TEST RESULTS - NORMAL STRESSES IN THE REINFORCEMENT

Fig. 3 shows the stress diagrams along the length of the insert located at the level z_2 = 0.29 m, depending on the load on the massif ceiling with a plate located at a distance of l_y = 0.30 m from the plane of the measuring wall. Two load values are considered: q = 37.02 kPa (curve I) and q = 61.69 kPa (curve II). The graphs show approximately the deformed axis of the reinforcement insert with the length la. The tensile stresses are marked as positive.

Fig. 4 illustrates the stress distribution along the length of the strips located at the depths of z_2 = 0.29 m and z_3 = 0.485 m, depending on the state of compaction of the soil massif. The plate exerting a load of q = 61.69 kPa was located at a distance of l_y = 0.30 m from the plane of the measuring wall. In the surface pre-compacted mass (curve *II*), the stress values in the reinforcement inserts are much lower than in the loosely poured soil (curve *I*).

Fig. 5 shows the distribution of normal stresses on the upper surface of the reinforcement inserts in a loose soil mass. The charts cover all five levels of the location of the reinforcement layers. The test load plate with the value q_{max} = 61.69 kPa shall be located l_y = 0.30 m from the plane of the test wall (diagram a) or l_y = 0.60 m = $l_{y,limit}$ (diagram *b*). The distance of the plate edge from the plane of the measuring wall l_y = 0.60 m is the limit, above which the soil pressure on the measuring wall has not been registered. It means that in this position of the slab, the fragmentation wedge in the soil mass is formed along the entire height of the model (*H* = 1.20 m - Fig. 1).

Fig. 6 shows (similarly to Fig. 5) graphs of the normal stress distribution on the upper surface of the inserts, arranged in layers on five measurement levels of the surface pre-compacted massif model. Two positions of the loading plate in relation to the plane of the measuring wall are considered: l_y = 0.30 m (diagram a) and l_y = 0.45 m = $l_{y,limit}$ (diagram b). The second location of the plate is the limit, above which there is no longer any value of soil pressure on the measuring wall (i.e., this position of the stamp is accompanied by a formed wedge of the fragment).

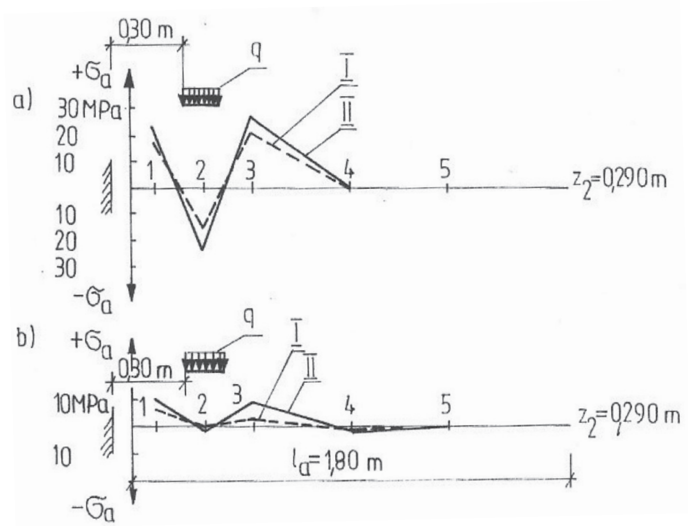

Fig. 3. Distribution of normal stresses on the upper surface of the reinforcement insert as a function of the test load value [15]: a - loose soil mass, b - surface pre-compacted, I - load q = 37.02 kPa, II - load q = 61, 69 kPa, 1-5 - numbering of strain gauges installed on the upper surface of the insert, z2 = 0.29 m - level of the insert location in the massif model, la - length of the reinforcement insert.

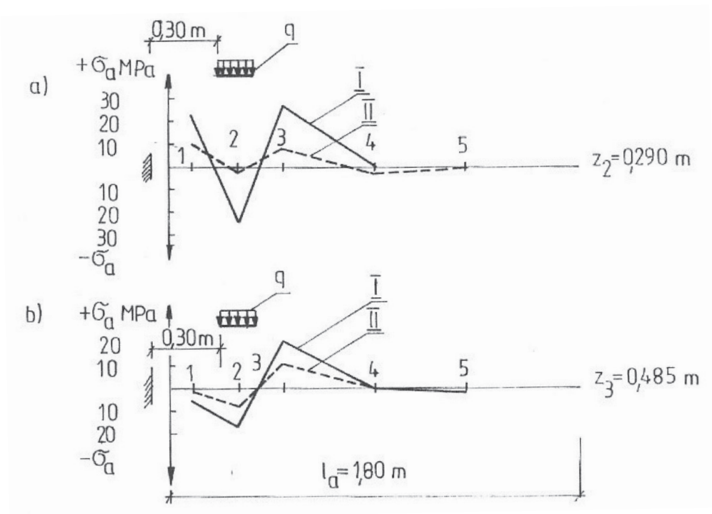

Fig. 4. Distribution of normal stresses on the upper surface of the reinforcement insert, located at the measurement level z2 = 0.29 m (a) and z3 = 0.485 m [15].
Test load q = 61.69 kPa, I - loose soil mass, II - surface pre-compacted, 1-5 - numbering of strain gauges installed on the upper surface of the insert,

la - length of the reinforcement insert.

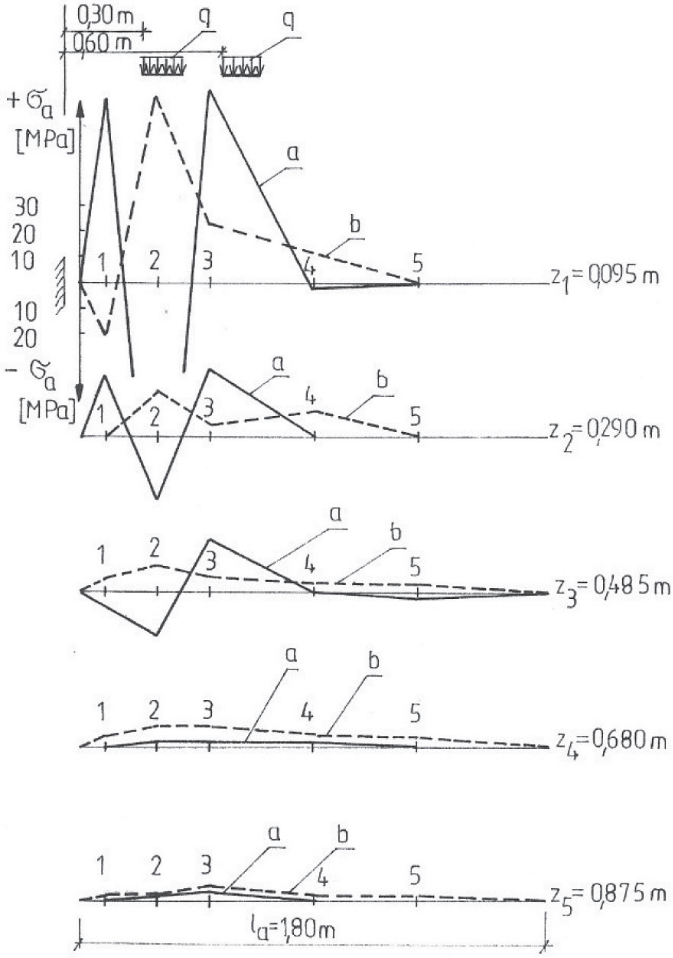

Fig. 5. Distribution of normal stresses on the upper surface of reinforcement inserts in a loose soil mass [15]:
a - diagram for the location of the loading slab at a distance of ly = 0.30 m from the plane of the retaining wall,
b - diagram for ly = 0 , 60 m = ly.limit test load q = 61.69 kPa; z1, z2, z3, z4, z5 - levels of locations of reinforcement layers,
1-5 - numbering of strain gauges installed on the top surface of the inserts,
la - length of the reinforcement insert.

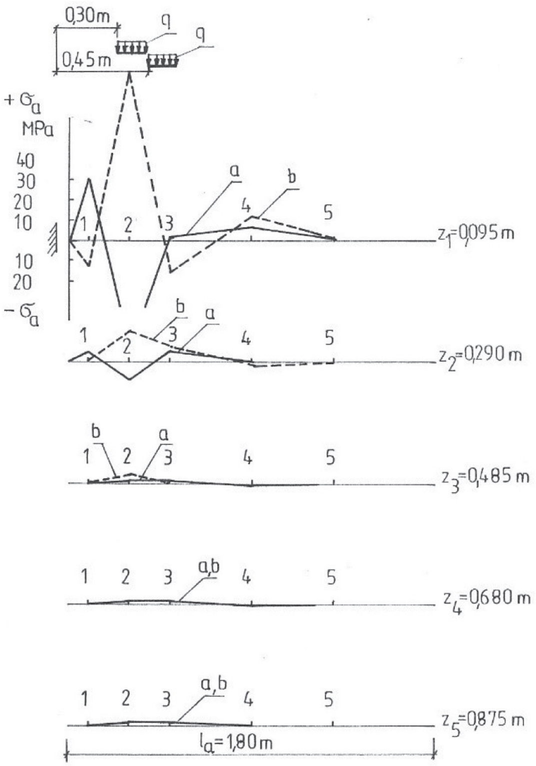

Fig. 6. Distribution of normal stresses on the upper surface of the reinforcement inserts in the surface pre-compacted soil mass [15]: a - diagram for the location of the load plate at a distance of ly = 0.30 m from the plane of the retaining wall, b - diagram for ly = 0.45 m = ly.limit , test load q = 61.69 kPa, z1, z2, z3, z4, z5 - levels of locations of reinforcement layers, 1-5 - numbering of strain gauges installed on the upper surface of the inserts, la - length of the reinforcement insert.

3. ESTIMATION OF THE LOCATION OF THE SLIP SURFACE

The results of the tests performed on the laboratory model of the massif made of reinforced soil allow to conclude that with the increase of the distance between the loading plate and the measuring wall, the deformation character of the reinforcement tapes changes. If the distance between the slab and the wall reaches the limiting value $l_y \approx l_{y,limit}$ (the slab locations $l_y \geq l_{y,limit}$ are not accompanied by any increases in soil pressure on the wall), then only tensile stresses will occur on the upper surface of the reinforcement strips. Such a state of stresses in the reinforcement may be confirmed by the fact that the splinter wedge was formed at the total height of the soil mass. The only exception are the inserts at the highest level (z_1 = 0.095 m), where the strain gauge No. 1 shows a compressive stress ($-\sigma_a$) on their upper surface. This phenomenon was repeated in all tests performed (assuming a variable number of inserts in the massif model) and is probably the result of a direct, disturbing influence of the plate loading the model.

In the reinforcement tapes located on the lower levels of the model (z_4, z_5 - e.g. Fig. 5), the stresses of one character (tensile) occur already at the distance of the loading plate edge from the retaining wall smaller than the limit $l_{y,limit}$. Therefore, it can be concluded that the destruction of the soil mass is progressive, i.e., that the fragmentation wedge is gradually formed, first obtaining the target shape in the lower zone.

French studies (eg [8, 9, 13]) proved that the potential slip curve at the stress limit equilibrium state can be obtained by plotting. It is the geometrical site of the maximum tensile forces occurring in the individual layers of the reinforcement. Proceeding analogously to the points of occurrence of the maximum ordinates, related to the b-curve in Fig.s 5 and 6, the course of the slip line in the reinforced sand massif was experimentally determined (Fig. 7). The accuracy of estimating the shape of this curve results, among others, from the number of strain gauge locations and their arrangement on the reinforcement tapes.

As it is known, reinforced soil exhibits the characteristics of anisotropic cohesion c *, defined by the relationship developed by the Laboratoire Central des Ponts et Chaussées (LCPC) in Paris [8, 9, 13]:

$$c^* = f_a \tan (450 + 0,5\ \phi)\ (2\ \Delta z)\text{-}1 \qquad (1)$$

wherein:
f_a - tensile strength of horizontal reinforcement layers [kN/m^{-2}],
ϕ - angle of internal friction of soil material [°],
Δz - vertical spacing of reinforcement layers [m].

Therefore, the suvbject slip curve should be identified as the line of destruction of the soil medium with cohesion.

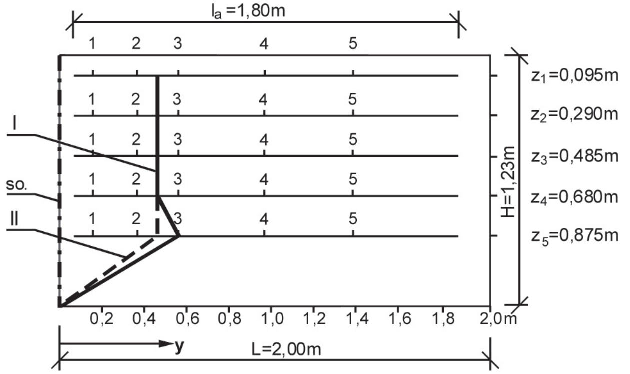

Fig. 7. The curve connecting the points of maximum tensile stresses in the reinforcement (approximate estimate) [14, 15]: 1-5 - numbers of strain gauges glued on the upper surface of the inserts, s.o. - retaining wall; z1, z2, z3, z4, z5 - numbers of the measuring levels of the retaining wall, I - loose sand massif, II - pre-compacted sand massif.

Research conducted in France (on the example of a massif with a vertical wall of reinforced soil in Dunkirk [9]) shows that in those structures whose upper surface is loaded, the stress distribution in the reinforcement (due to gravity and external load) is of the same nature as in unloaded retaining structures. Therefore, the research concept adopted by the authors of this article, consisting in the use of a special research load on the model ceiling (with a minimum but necessary *q* value) in order to excite the splinter wedge, is correctly oriented.

The research of N. T. Long [9] also proved that the location of the slip line, i.e. the line of maximum tensile stresses (separating the active zone from the soil resistance zone) in an externally loaded soil mass, may be different than in the case of an unloaded massif (Fig. 8a, b). It depends on the ratio of the magnitude of the external load *Q* to the own weight of the soil material forming the mass, and on the place where the load is applied in relation to the face of the wall. Fig. 8 shows the lines connecting the points of maximum tensile stresses in the reinforcement of the massif. These are the results of research conducted on theoretical models using the finite element method. However, N. T. Long does not provide the exact value of this quotient, using only the expression [9]: "high" or "small" load. If the load *Q* is relatively large and applied near the wall, it can be assumed, according to N. T. Long, that the boundary between the two zones in the upper part of the massif approaches the point where the load Q is applied (Fig. *8b - curve 1*).

The course of the curve (1) in Fig. 8b is similar to the slip curve obtained as a result of strain gauge tests (Fig. 7). As previously mentioned, the special test load q [kPa] was selected as a result of the tests performed and is characterized by the minimum value possible, at which the goal of the task was achieved, while taking into account the technical constraints (concerning the physical model of the massif with reinforcement) [15].

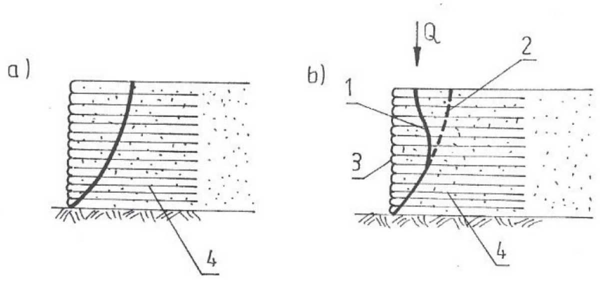

Fig. 8. Location of points corresponding to the maximum tensile stress in the reinforcement (theoretical models, calculation results obtained using the finite element method) [9]:
a - unloaded massif, b - massif loaded with concentrated force Q, 1 - diagram for a case of a significant load applied near a wall, 2 - a small load case, 3 - vertical massif wall, 4 - reinforcement inserts.

4. CONCLUSIONS

The size and shape of the fracture wedge in the soil mass with reinforcement was estimated in the case of the boundary state of active pressure on the retaining wall. The task was performed experimentally, on the basis of measured deformations of the reinforcement inserts, with the use of electrofusion strain gauges. The points of maximum normal stresses occurring in the reinforcement inserts, which are located in the horizontal layers, create the slip curve. This curve cuts off the fragment wedge that is being sought from the plane of the retaining wall. The slip curve divides the massif area into two zones: active (splinter wedge) and passive, in which the inserts are anchored.

The usefulness of electrofusion extensometry in research on the functioning of exploited reinforced soil retaining structures used in civil engineering was demonstrated. The measurement of normal stresses in the reinforcement allowed for a fairly precise determination of the shape of the slip surface in the physical model of the soil mass, prepared on a laboratory scale.

REFERENCES

[1] Bacot I., Lareal P., *Etude sur modeles reduits tridimensionneles de la nysture de massifs en*

[2] Clayton C. R. J., Milititsky J., Woods R. J., *Earth Pressure and Earth Retaining Structures*, Blackie Academic & Professional, London–New York 1996.

[3] Corte J., *La methode des elements finis appliguee aux ouvrages en terre armée*, "Bulletin de liaison des laboratoires routiers: ponts et chaussées, 90 (1977)/7-8, pp. 37-48.

[4] Horvath J. S., Regins J., Colasanti P. E., *New Hybrid Subgrade Model for Soil-Structure Interaction Analysis: Foundation and Geosynthetics Applications*, [in:] *ASCE Geo-Institute/IFAI/GMA/NAGS: Geo-Frontiers 2011, Dallas, Texas, USA, 13-16 March 2011*, 2011, pp. 1-11.

[5] Ingold T. S. (ed.), *The Practice of Soil Reinforcing in Europe*, Thomas Telford, London 1996.

[6] Jones C. J. F. P., *Earth Reinforcement and Soil Structures*, Thomas Telford, London 1996.

[7] Leśniewska D., Kulczykowski M., *Grunt zbrojony jako materiał kompozytowy. Podstawy projektowania konstrukcji*, Wydawnictwo Instytutu Budownictwa Wodnego Polskiej Akademii Nauk, Gdańsk 2001.

[8] Long N. T., Schlosser F., *Zasada działania i zachowanie się gruntu zbrojonego,* [in:] *Wybrane zagadnienia geotechniki*, red. Maziarz K., Wydawnictwo Instytutu Budownictwa Wodnego Polskiej Akademii Nauk, Ossolineum, Wrocław–Warszawa 1978, pp. 157-184.

[9] Long N. T., *Badania gruntów zbrojonych*, [in:] *Wybrane zagadnienia geotechniki*, red. Maziarz K., Wydawnictwo Instytutu Budownictwa Wodnego Polskiej Akademii Nauk, Ossolineum, Wrocław–Warszawa 1978, pp. 185-210.

[10] Long N. T., Schlosser F., *Wymiarowanie murów z gruntów zbrojonych*, [in:] *Wybrane zagadnienia geotechniki*, red. Maziarz K., Wydawnictwo Instytutu Budownictwa Wodnego Polskiej Akademii Nauk, Ossolineum, Wrocław–Warszawa 1978, pp. 211-237.

[11] Sawicki A., *Statyka konstrukcji z gruntu zbrojonego*, Wydawnictwo Instytutu Budownictwa Wodnego Polskiej Akademii Nauk, Gdańsk 1999.

[12] Sawicki A.; *Mechanics of Reinforced Soil*. A.A. Balkema, Rotterdam/Brookfield, 2000.

[13] Schlosser F., *La terre armée. Recherches et realisations*, "Bulletin de liaison des laboratoires routiers: ponts et chaussées, 62 (1972)/11-12, pp. 79-92.

[14] Surowiecki A., *Multiscale modelling in railway engineering. Researches and technology,* [in:] *Proceedings of the 16th French-Polish Colloquium, Laboratoire de Méchanique & Génie Civil, July 12-15, 2013*, Montpellier 2013.

[15] Surowiecki A., *Komunikacyjne budowle ziemne ze wzmocnieniem skarp. Badania modelowe nośności i stateczności*, Wydawnictwo Wyższej Szkoły Oficerskiej Wojsk Lądowych im. gen. T. Kościuszki, Wrocław 2016.

[16] Wiłun Z., *Zarys geotechniki*. Wydawnictwo Komunikacji i Łączności, Warszawa 2016.

[17] Zamiar Z., *Odbudowa infrastruktury transportowej,* [in:] *Zborník z 10. vedeckej konferencie Crisis Management, Žilinská Univerzita v Žiline*, Žilina 2006.

[18] Zamiar Z., *Infrastruktura transportu – wybrane zagadnienia*, Biblioteka Międzynarodowej Wyższej Szkoły Logistyki i Transportu we Wrocławiu, CL Consulting & Logistyka, Oficyna Wydawnicza NDiO, Wrocław 2011.

[19] Zamiar Z., *Infrastruktura transportu jako element infrastruktury krytycznej,* Biblioteka Międzynarodowej Wyższej Szkoły Logistyki i Transportu we Wrocławiu, CL Consulting & Logistyka, Oficyna Wydawnicza NDiO, Wrocław 2011

[20] Zamiar Z., Bujak A., *Zarys infrastruktury i technologii przewozów podstawowych gałęzi transportu*, Biblioteka Międzynarodowej Wyższej Szkoły Logistyki i Transportu we Wrocławiu, CL Consulting & Logistyka, Oficyna Wydawnicza NDiO, Wrocław 2007.

[21] Zamiar Z., Surowiecki A., Saska P., *Infrastruktura transportowa*, Biblioteka Międzynarodowej Wyższej Szkoły Logistyki i Transportu we Wrocławiu, Oficyna Wydawnicza ATUT, Wrocławskie Wydawnictwo Oświatowe, Wrocław 2020.

Zenon Zamiar
The International University
of Logistics and Transport in Wrocław, Poland
zzamiar@msl.com.pl
ORCID: 0000-0001-9887-0183

Andrzej Surowiecki
General Tadeusz Kościuszko Military University
of Land Forces in Wrocław, Poland
andrzejsurowiecki3@wp.pl
ORCID: 0000-0003-4080-3409