10.26411/83-1734-2015-2-51-6-21

Research on vertical displacements of an experimental section of a railway track with a spatial mat reinforcement

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 are the layers strengthening the base of the railway track, used in special cases of modernization of the main lines on the Polish State Railways. The construction of a three-dimensional reinforcing mat, also known as a "mattress", is presented. The reinforcing "mattress" is a layer of stone aggregate pre-compressed in an openwork coating made of plastic mesh.

The results of the research on vertical displacements of the experimental section established in the railway track with a spatial mat embedded in the substrate are discussed. Vertical displacements were obtained as a function of time in the track subjected to the operation process.

Keywords: three-dimensional mat, ground reinforcement, field tests

1. INTERMEDIATE LAYERS AS TRACK BED REINFORCEMENT

The problem of strengthening the subsoil has been present on Polish railways for many years, due to the necessity to adapt the main lines to the technical standards in force on Western European railways [1, 2, 13, 25-29].

The standard for the modernization of railway lines is a multi-layer track structure, in which individual layers can fulfill various tasks [2, 13, 18, 23]. There are a number of proposals for the design of the track base in the track zone. They differ in details, but they aim to achieve the basic goal: the required bearing capacity [13, 18, 21, 23]. In many cases, to obtain the appropriate load capacity of the track, it is necessary to strengthen the subsoil, which is the track foundation. The existing methods of strengthening the subsoil can be divided into two groups [3, 18, 24]: physical-mechanical and physical-chemical strengthening. The physical and mechanical reinforcement includes, among others Reinforced soil system (soil medium cooperating with tensile stress-absorbing inserts), which was proposed in this article. In the field of reinforced soil technology, developed in France [4, 10, 11], the current state of knowledge is based on very advanced studies of physical models on a laboratory scale, field studies (on real objects) and numerical analyses [4-6, 9, 12, 14, 16, 17, 19-22].

Figure 1 shows a proposal for the development of a geotextile and geogrid prepared in Wrocław in the track of the modernized E59 main line on the Wrocław-Poznań section. The task of the geotextile is to separate the track structure from the subsoil (containing cohesive soils which are impermeable material) and to discharge water from precipitation outside the track. The geogrid, on the other hand, takes over the tensile stresses occurring at the track level, generated by the operational load.

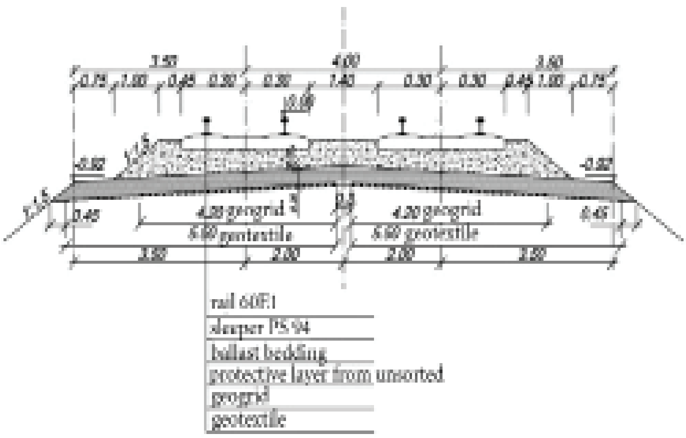

Fig. 1. Cross-section through a railway line with layers strengthening the track base.
Source: DOLKOM - Lower-Silesian Company for the Transport Infrastructure Repair in Wrocław

2. THREE-DIMENSIONAL COMPOSITE TO STRENGTHEN THE TRACK BED (CONSTRUCTION AND PRINCIPLE OF OPERATION)

On the Polish State Railways network, during the modernization of the C59/2 railway line Wrocław-Międzylesie, a spatial mat, known as a "mattress", was installed in the ground. The "mattress" consists of two elements [18]:

1. a layer of stone aggregate (basalt crushed stone, grain size 31.5 ÷ 50.0 mm; angle of internal friction in a moderately compacted state φ = 37.90), filling the mattress space and characterized by a significant value of the angle of internal friction in relation to the friction angle soil in the track substrate,
2. "compressing" stone aggregate coating, made of the FORTRAC® system geogrid, type R 90 / 90-20T [8], with technical characteristics: plastic-polyester, polymer coating, tensile strength in the longitudinal and transverse direction Rr 90 kN /m , max elongation at break in both directions Δl ≤ 10%, square mesh size 20 x 20 mm. The mesh size of the geogrid was adjusted to the size of the aggregate grains in order to ensure the desired sliding resistance in the coating plane. The effect of the so-called wedging grains.

The thickness of the aggregate layer filling the mattress was assumed in the range of hm = 0.15-0.20 m. This value was estimated based on theoretical and experimental analysis, taking into account, inter alia, dynamic nature of the operational load, technical parameters of the track surface and bearing capacity of the subsoil (diagnosed as a weak subsoil). The "mattress" was placed on a base layer made of aggregate (which is a waste material), spread over the surface of the track. The cooperation between this layer and the "mattress" is realized by the principle of friction in the plane of the bottom mattress shell.

Tasks performed by the "mattress" [18]:

- reducing track subsidence,
- transferring the operational loads to the ground in an even manner,
- protection against contamination of the stone aggregate, which is the track ballast, by particles of the weak subsoil (Fig. 2). The "mattress" may constitute an active separation layer, i.e. an effective barrier against the vertical penetration of the watered cohesive soil medium into the bedding layer under the sleepers.

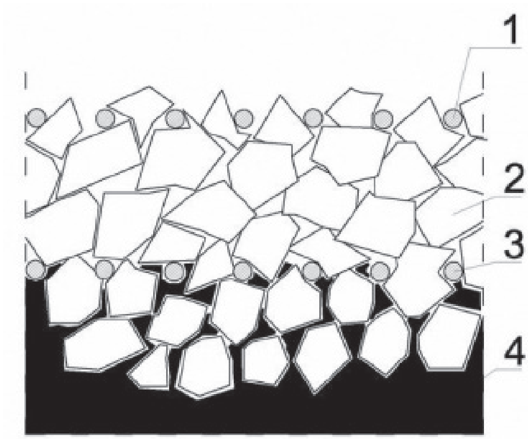

Fig. 2. Vertical section through a "mattress" that strengthens the substrate. The "mattress" protects against penetration of the liquefied subsoil material in the direction of the track bed: 1 - the rod of the upper surface of the mattress, 2 - the crushed stone filling the mattress space, 3 - the rod of the lower surface of the mattress, 4 - the liquefied material of the subsoil of the track.
Source: own study

Fig. 3 illustrates one of the structural forms of a strengthening "mattress" used in selected locations, on the Wrocław-Międzylesie section along the C59 / 2 main [18].

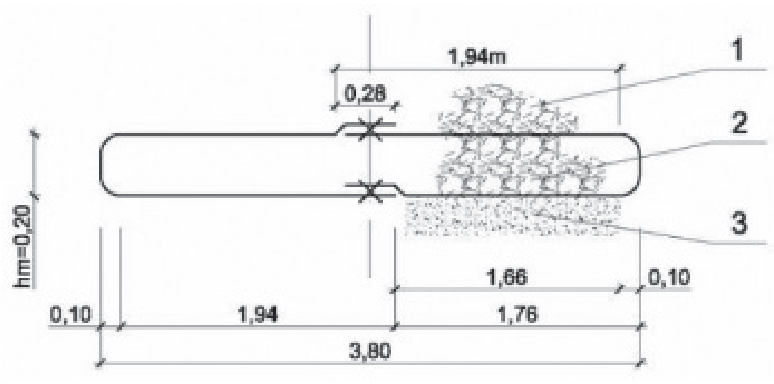

Fig. 3. Vertical cross-section through the reinforcing mattress [18]: 1 - ballast bedding, 2 - crushed stone filling the mattress space, 3 - protective layer made of waste material.
Source: own study

3. INVESTIGATION OF VERTICAL DISPLACEMENTS OF THE EXPERIMENTAL SECTION OF THE TRACK WITH THE REINFORCING LAYER IN THE SUBSTRATE

Introductory note

The results of long-term (12-15 months) measurements of subsidence of a railway track section are presented. The track is situated on impermeable clay substrate. The reinforcing layer in the form of a "mattress" is installed directly under the ballast bed [18].

Location of the object and the existing state

The experimental section was located in the junction zone, located in the main track of the Boreczek PKP station, on the C59 / 2 main route Wrocław-Międzylesie-Lichkov-Prague [18]. The station area is situated on clay soil. Macroscopic examinations of soil samples taken to a depth of 1.2 m under the station track and turnout showed the presence of contaminated plastic clay [7, 24]. There is no free drainage of rainwater outside the track area here. Water penetrates through the ballast into the clay substrate. The clay becomes plasticized and under the cyclical pressure of operational load it is pressed between the ballast grains of the ballast, which is one of the reasons for uneven track settlement. On the considered section of the track, about 150 m long, including the turnout, traces of liquefied clay from the track bed were visible on the upper surface of the concrete sleepers. Numerous scratches and cracks in these sleepers indicated uneven subsidence of the track section. As a result, the station track, especially in the junction zone, required frequent profile adjustments and quite often the introduction of speed limits.

Construction of a reinforcing layer in the form of a mattress

The mattress (a separate reinforcement unit) was made of two horizontal plastic meshes (FORTRAC® system, type R 90 / 90-20T [8]), separated by a layer of stone aggregate. Reinforcing meshes form a closed mattress shell (Fig. 4 [8, 18]).

In order to ensure the appropriate quality of interaction of the two reinforcement layers (forming the mattress coating), a mattress with a thickness of h_m = 0,15 m was designed. The material filling the mattress space is basalt crushed stone 20/60, pre-compacted in the mesh coating (the initial stress of the coating was performed during assembly).

The effect of the reinforcement mattress under the ballast bedding layer is equivalent to that of the h_0 [m] thick reinforcing layer made of aggregate (crushed stone). This thickness can be calculated, for example, from the formula developed by the Hungarian Railway Institute (VTKI) [18]. In this formula, the parameter q_{kr} appears as the track load that does not make the subsoil plastic. The value of this load in the critical elastic state was calculated from the formula O.K. Fröhlich [18, 24]. For the track section in question, the subsoil (made of plastic clay) is characterized by the following features: internal friction angle $\varphi = 12^{\circ}$, cohesion $c = 0.02$ MPa.

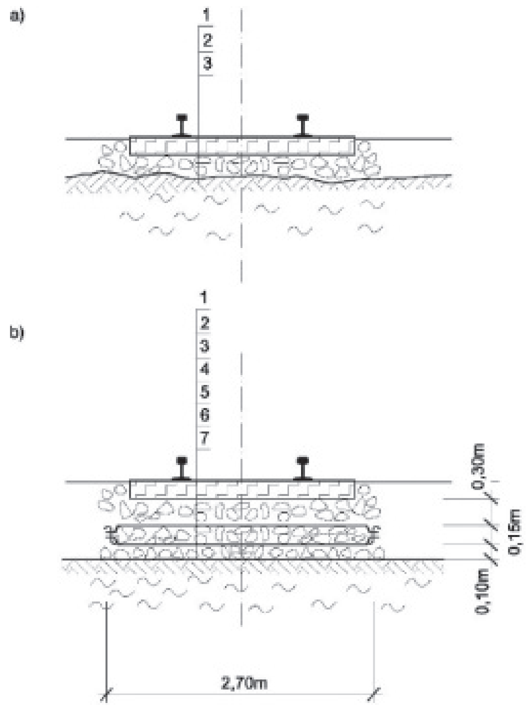

Fig. 4. Cross-section of the track in the experimental section: a - before the renovation, 1 - base, 2 - ballast, contaminated with clay, 3 - soil substrate (clay); b - after renovation (designed layout of track foundation layers), 1 - sleeper, 2 - ballast made of gravel with a layer thickness of 0.3 m; 3 - upper mesh of the mattress, 4 - a layer of crushed stone filling a mattress with a thickness of 0.15 m; 5 - bottom mesh of the mattress, 6 - levelling layer 0.1 m thick made of crushed stone; 7 - soil substrate (clay)
Source: own study

Other data:

g_n = 0.02 MPa - stresses in the soil medium of the track crown, resulting from the own weight of the pavement (calculations can be found in monograph [18]),

b = 0.24 m - sleeper width,

k_v = 2.0 - dynamic coefficient,

$\sigma_0 = P \cdot (A)^{-1} = 3{,}36 \cdot 10^5$ N/m^2 - vertical stress in the ballast at the level of the underside of the sleepers, assuming that the pressure of the railway vehicle P is transferred to one sleeper with surface A ($A = b \cdot l_p$, where l_p is the length of the sleeper),

a = 0.65 m - axial distance of sleepers,

U = 200 MPa - rail base stiffness coefficient (the value was adopted according to [18]),

$w_{r,n}$ = 0.27 - stress distribution coefficient in the ballast (the value was adopted according to [18]),

h_t = 0.3 m - thickness of the ballast layer under the track sleeper.

From the formula of O.K. Fröhlich [18, 24], the value of the critical load on the track is obtained, which is the maximum vertical stress: $q_{kr} = p_{z,max} = 9{,}43 \cdot 10^4$ N/m^2. After substituting these data into the VTKI formula [18], the thickness of the reinforcement layer h_0 = 0.55 m was obtained. The track load q_{kr} was checked using L. Prandtl's formula [18, 24], from $q_{kr} = p_{z,max} = 9{,}39 \cdot 10^4$ N/m^2, after applying the safety factor $n = 2$. Then the necessary thickness of the crushed stone reinforcement layer is h_0 = 0.554 m. This thickness is almost four times greater than the required thickness of the designed reinforcement mattress h_m = 0.15 m.

The technique of embedding a reinforcement mattress

Figure 5 shows the situational plan of the experimental section installed in the junction zone (right ordinary turnout) [18]. The length of the track zone (*a*) subjected to renovation (consisting in the replacement of rails, sleepers and ballast) and the range of the mattress zone (*b*) about 39.0 m long were marked, and the location of the measurement sections was shown, which were assumed at the average distances: *e* = 2.5 m. Each measurement section had two (measurement) points; one on the rail head of each rail - west "w" and east "o". After the demolition of the existing turnout and adjacent track sections, the contaminated ballast and the upper layer of contaminated clay bed were removed. Then a layer of the so-called underlay crushed stone with a thickness of ≤ 0.1 m and compacted with multiple passes of a tracked vehicle. After unfolding the lower mesh of reinforcement, a layer of 0.15 m thick crushed stone filling the inside of the mattress was scattered along the track axis. The aggregate was compacted and then covered with a mesh identical to the bottom mesh. The pretension of the mattress was performed by creating tension in the nets (which constitute the mattress cover) by rigidly connecting the contacting edges of the meshes: the upper and lower ones, with the use of appropriately formed steel wire clips. Such connections were made at 0.5 m intervals along the entire length of the mattress. After the top mattress mesh was covered with ballast and the surface was laid, the track was adjusted in the plan and profile by running a specialist machine twice (for example, the ballast was compacted twice under the sleepers in the rails zones).

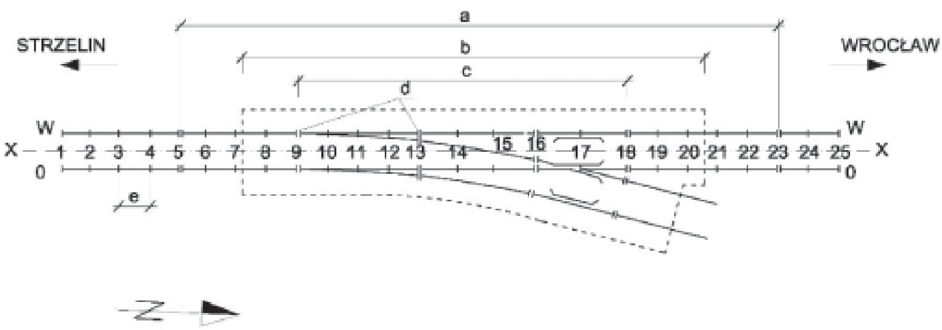

Fig. 5. Site plan of the experimental stage: *a* - renovated 49.0 m long track zone, *b* - range limit of a reinforcement mattress, *c* - turnout, *d* - classic rail contacts, 1, 2,… 25 - measurement cross-sections situated perpendicularly to the x - x longitudinal axis of the main track. Each vertical measurement section has one measurement point on the rail head of the western *(w)* and eastern *(o)* course, *e* - distance between the measurement sections (2.5 m on average)
Source: own study

The course of research

The study of the behaviour of the experimental section in the turnout of the station track under operational load consisted in performing levelling measurements of the settlement of the measurement points adopted on the track heads in both runs. Intensive measurements were performed for a period of 10 months, starting from the moment of placing the "mattress" [18].

Findings

Figure 6 shows the graphs of the average track settlement as a function of time for the measurement sections outside the rail joints: above the mattress (No. 8, 11, 17, 20) and sections outside the mattress (No. 6 and 22) [18]. Settlements in each measurement section were calculated as the mean of both railways ("w" and "o"). The track subsidence is even above the mattress. However, apart from the mattress, they are larger and differ significantly from each other.

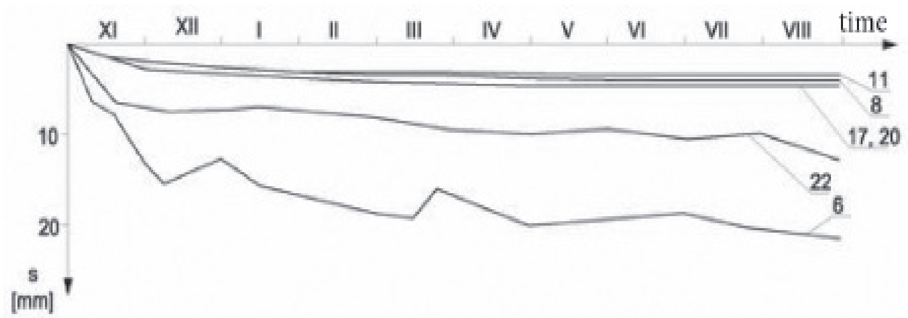

Fig. 6. Graphs of the average track settlement as a function of time:
No. *8, 11, 17, 20* - measurement cross-sections
above the mattress outside the contacts, no. *6, 22* - outside the mattress
and outside the contacts
Source: own study

Fig. 7 presents graphs of the average track settlement as a function of time for the measurement sections in the rail joints: above the mattress (No. 9 and 18) and outside the mattress (No. 5 and 23) [8]. The nature of subsidence in the sections outside the mattress is uneven.

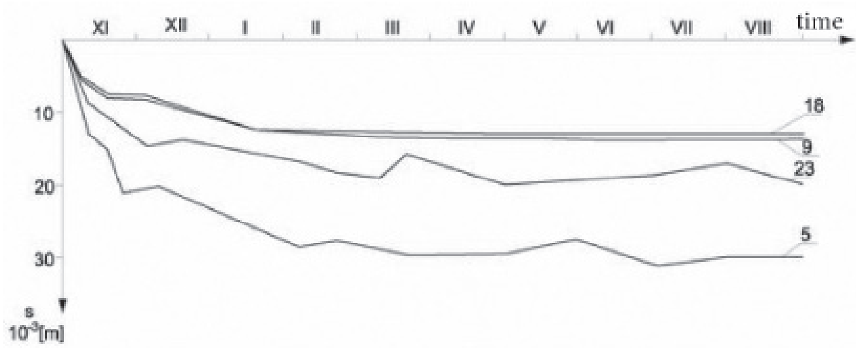

Fig. 7. Graphs of the average track settlement as a function of time: No. *9, 18* - track in the joints of rails above the mattress,
5, 23 - track in the rails' joints outside the mattress
Source: own study

The modulus of deformation of the soil layer in the track bed

The strength of soils due to the external load can be assessed with the modulus of deformation. If at a certain depth in the soil medium there are vertical compressive stresses σ_z, causing a deformation of the layer with the thickness h of the soil medium by the amount δh, then the deformation modulus E_d is [18, 24]:

$$E_d = \sigma_z \cdot h \cdot (\delta h)^{-1} \quad (1)$$

The values of this module, calculated for the following data: $\sigma_z = \sigma_0 = 3{,}36 \cdot 10^5$ N/m^2, $h_p = h_t + h_m = 0{,}30 + 0{,}15 = 0{,}45$ m (thickness of the bedding layer plus the thickness of the reinforcement mattress) , and for total settlements, $\delta h = s$ (measured after 10 months of track operation) are as follows:

1. for a track section beyond the rail contacts:
   - track on a reinforcement mattress: $E_d^* = 182{,}17 \cdot 10^5$ N/m^2,
   - track outside the reinforcement mattress: $E_d = 50{,}40 \cdot 10^5$ N/m^2,
2. for a track section in rail contacts:
   - track on a reinforcement mattress: $E_d^* = 55{,}38 \cdot 10^5$ N/m^2,
   - track outside the reinforcement mattress: $E_d = 30{,}24 \cdot 10^5$ N/m^2.

The effectiveness of the mattress in terms of the enlargement of the deformation modulus was assessed by the $W_{e,m}$ index, which is the quotient of the deformation modules [18]:

$$W_{e,m} = E_d^* \cdot (E_d)^{-1} > 1,0 \quad (2)$$

For the track apart from the rail contacts, this index is: $W_{e,m}$ = 3.61, and for the track in the contacts: $W_{e,m}$ = 1.83, i.e. the efficiency in the second case is lower by about 50%.

Track twist

Based on the results of the tests of vertical track displacements along the length of the renovated section, the track twist was calculated according to [18], as the variable height difference of one rail track over the other, in relation to the length on which this difference occurs.

Table 1 summarizes the results of the track twist calculations in the experimental section after two, four, six, eight and ten months of track operation, from the day of its major renovation [18]. These values were calculated assuming the distance between two consecutive measurement sections as the base length, which is 2.5 m. The numerical values of twist justify the use of a reinforcement mattress in the railway track base.

Table 1. The results of the track twist calculations in the experimental section [18]

Period of the track exploitation (months)	Type of Object	
	Track section outside the joints	
	on the mattress	outside the mattress
2	0.14	1.20
4	0.17	1.80
6	0.17	1.42
8	0.20	3.10
10	0.20	3.86

4. SUMMARY

The track on the strengthening mattress, placed under the bedding layer, shows even settlement in the section at the classic joints of rails and outside the joints. The values of these settlements are much lower in relation to the subsidence of the track without the reinforcement mattress.

The value of the modulus of deformation of the track bed with a reinforcement layer is definitely higher than the modulus of the track bed made of unreinforced material.

The reinforcement layer introduced in the track bed contributes significantly to reducing the twist of the track. As a result, it is possible to extend the service life of the track between repairs and at the same time increase the economy of track maintenance.

REFERENCES

[1] Bałuch H., Bałuch M., *Układy geometryczne toru i ich deformacje*, Wojskowa Akademia Techniczna, Warszawa 2010.

[2] Bogdaniuk B., Towpik K., *Budowa, modernizacja i naprawy dróg kolejowych*, Kolejowa Oficyna Wydawnicza, Warszawa 2010.

[3] Bzówka J., Juzwa A., Knapik K., Stelmach K., *Geotechnika komunikacyjna*. Wydawnictwo Politechniki Śląskiej, Gliwice 2012.

[4] Corte J. F., *La methode des elements finis appliguee aux ouvrages en terre armee,* "Bulletin de Liaison des Laboratoire Routiers des Ponts et Chaussees", 90 (1977)/7, pp. 37-48.

[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] Eurocode 7. Projektowanie geotechniczne, cz. 1: Zasady ogólne, PN-EN 1997-1, V. 2008., cz. 2: Rozpoznanie i badanie podłoża gruntowego, PN-EN 1997-2, IV. 2009.

[8] Geosiatki FORTRAC® w konstrukcjach z gruntów zbrojonych, Przedsiębiorstwo Realizacyjne INORA® Sp. z o.o. , 44-101 Gliwice 1, ul. Prymasa S. Wyszyńskiego 11, 44-101 Gliwice 1 – www.inora.com.pl

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

[10] Long N. T., Schlosser F., *Zasada działania i zachowanie się gruntu zbrojonego. Wybrane zagadnienia geotechniki,* Wydawnictwo Instytutu Budownictwa Wodnego Polskiej Akademii Nauk, Wrocław-Warszawa 1978.

[11] Long N. T., *Badania gruntów zbrojonych. Wybrane zagadnienia geotechniki,* Polska Akademia Nauk, Wydawnictwo Instytutu Budownictwa Wodnego Polskiej Akademii Nauk, Wrocław-Warszawa 1978.

[12] Maro L., *Konstrukcje ziemne zbrojone geosyntetykami w budownictwie drogowym,* Wydawnictwo LEMAR, Łódź 2008.

[13] Massel A., *Projektowanie linii i stacji kolejowych*, Wojskowa Akademia Techniczna, Warszawa 2010.

[14] Pisarczyk S., *Geoinżynieria. Metody modyfikacji podłoża gruntowego,* Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2014.

[15] *Poradnik wzmocnienia podłoża gruntowego dróg kolejowych,* red. Biedrowski Z., Wydawnictwo Politechniki Poznańskiej, Poznań 1996.

[16] Sawicki A., *Mechanics of Reinforced Soil,* CRC Press, Rotterdam 2000.

[17] Surowiecki A., Ryczyński J., *Theoretical model of interaction of basic components of railway surface,* [in:] *Transport Means 2015: proceedings of the 19th International Scientific Conference, October 22-23, 2015, Kaunas, Lithuania,* Kaunas 2015, pp. 513-517.

[18] Surowiecki A., *Modernizacja konstrukcji dróg szynowych. Badania modelowe i eksploatacyjne*. Wydawnictwo Wyższej Szkoły Oficerskiej Wojsk Lądowych im. gen. T. Kościuszki, Wrocław 2012.

[19] Surowiecki A., *Multiscale modelling in railway engineering,* "Logistics and Transport", 21 (2014)/1, pp. 101-104.

[20] Surowiecki A., *Laborversuche zum Einfluss ausgewählter Parameter auf die Wirkung der Bewehrung in lockeren Böden,* "Bauingenieur", (1989)/5, pp. 215-217.

[21] Surowiecki A., *Interaction between reinforced soil components,* "Studia Geotechnica et Mechanica", 20 (1998)/1-2, pp. 43-61.

[22] Surowiecki A., *Multiscale modelling in railway engineering. The investigations and technology,* [in:] *Proceedings of the 16th French-Polish Colloquium, Laboratoire de Mécanique & Génie Civil, 12-15 Juillet 2013, Montpellier,* Montpellier 2013.

[23] Towpik K., *Koleje dużych prędkości. Infrastruktura drogi kolejowej,* Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2013.

[24] Wiłun Z., *Zarys geotechniki,* Wydawnictwa Komunikacji i Łączności, Warszawa 2010.

[25] Zamiar Z., *Odbudowa infrastruktury transportowej,* [in:] *Zborník 10. medzinárodnej konferencje Riešenie krízových situácii v špecifickom prostredí 2006, Žilinská univerzita*

v Žiline, Slovenská republika, Žilina, EDIS vydavateľstvo Žilinskej Univerzity, Žilina 2006.

[26] Zamiar Z., *Infrastruktura transportu. Wybrane zagadnienia,* CL Consulting i Logistyka, Oficyna Wydawnicza NDiO, Wrocław 2011.

[27] Zamiar Z., *Infrastruktura transportu jako element infrastruktury krytycznej,* CL Consulting i Logistyka, Oficyna Wydawnicza NDiO, Wrocław 2011.

[28] Zamiar Z., Bujak A., *Zarys infrastruktury i technologii przewozów podstawowych gałęzi transportu,* CL Consulting i Logistyka, Oficyna Wydawnicza NDiO, Wrocław 2007.

[29] Zamiar Z., Surowiecki A., Saska P., *Infrastruktura transportowa*, 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