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The dependence of the state density of subgrade on the state of its deformability

Abstract: The paper discusses the method of performing and elaboration of measurement of subgrade deformability. It was shown the required values of deformation modules of as well as density and deformation indexes. The analysis of stress and deformation of laminar subgrade has been made in order to determine the depth of interaction zone on a test plate in the subgrade. Presented conclusions regard to the applicability of normative dependencies on the value of deformation and density index.

Keywords: Railroad; Railway Subgrade; Density of subgrade

Introduction

Modernization of railway road includes also the reconstruction of subgrade, which relies mainly on strengthening its upper zone under the surface, by building a protective layer, after the preparation of the existing subgrade. The subgrade, also in the track area, is composed of various mineral and even organic grounds, and is characterized by heterogeneity of physical and mechanical properties. The use of the protective layer can significantly reduce the material inhomogeneity of the subgrade under the surface, with simultaneous improving the physical and mechanical properties required by the rules, i.e. the density and deformability of the new system. The new state of subgrade during construction and after its completion is controlled in geotechnical studies to determine the density index and deformability modules of the soil substructure and the protective layer. The degree of compaction is determined during laboratory testing on the basis of soil samples with intact structure, taken from construction sites of ground or the protective layer in the evaluated state, by comparison with the state achieved in the laboratory. Primary and secondary deformation modules are determined from the results of test loads on the subgrade with the plate VSS. The values of density ratios and secondary deformation modules are compared with the values present in railway regulations and projects of subgrade reconstruction.

Laboratory studies of grounds and materials specifying the density indexes are cumbersome, time-consuming and costly, whereas sampling coarse-grained soil and their transport is difficult and can lead to erroneous results. In addition, methods for determining the density ratio of ground are useful for testing aggregates produced in the quarries (eg. unsorted stones) only in a limited extent. These difficulties are so significant that it is assumed an indirectly assessment of the state of soil compaction and materials of protective layers using the deformation ratio for practical applications during the substructure works and their acceptance, as well as in the construction of car roads. The values of deformation ratio are expressed as the ratio of primary and secondary deformation, are calculated from the same VSS sample and have the value of the density index of the subgrade plate corresponding to the standard [6]. This indirect method of assessing compaction of subgrade soil and materials of protective layers is currently the most widely used in the modernization of the subgrade.

The presented method of assessing compaction of soil subgrade and materials of protective layers, however, has some important limitations. The source of these limitations is stated in the standard value of deformation index relating to the homogenous medium loaded by the test plate. Real systems of materials from protective layers and grounds of the existing subgrade are not homogenous. The uncritical transfer of such prepared standard values to real systems of layered subgrade with geosynthetics requires analysis and discussion. In current practice during the modernization of subgrade it was achieved values of the deformation index different from those reported in the standard. Analysis of the results was carried out on the basis of the state of stresses and strains in the subgrade loaded by the plate VSS.

Deformation modules and strain index

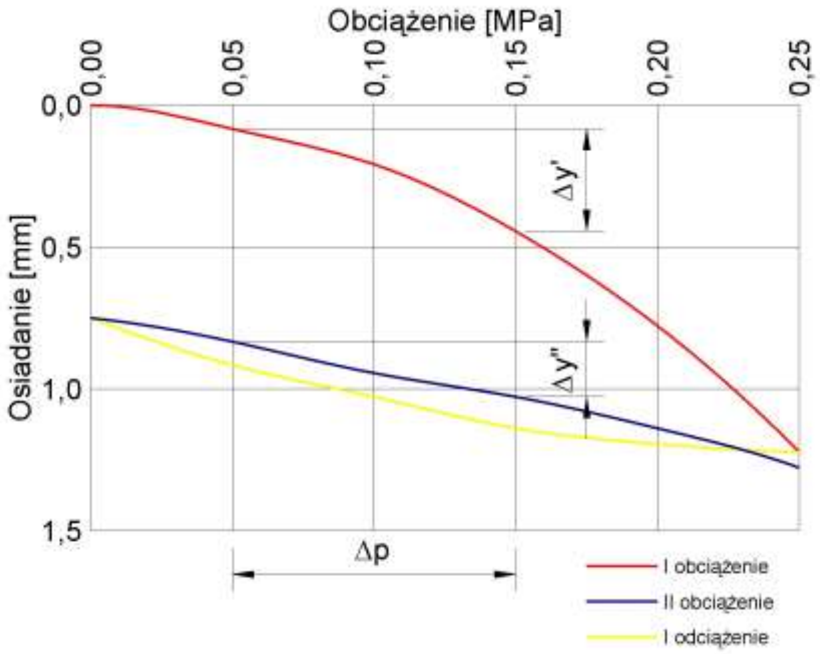
The measure of deformability is the ratio of the unit surface load transferring the load to its settlement under the load, with regarding geometrical and physical conditions of the measurement. For the purposes of road construction, the test load is performed with the steel round plate in order to determine the initial modulus of ground deformation *E*' and quasi elastic modulus *E*" from the second load.

The value of deformation modulus based on the load with round plate is given by [6], [4]:

$$E = 0{,}75 \cdot \frac{\Delta p}{\Delta y} \cdot D \quad (1)$$

where: E – deformation modulus [MPa], D – plate diameter [mm], Δ_p – interval of load assumed for computation of the module [MPa], Δ_y – settling plates in the assumed range of loads [mm]

An integral part of the test is the greatest pressure transmitted on the ground through the plate (p_{max}) and load interval (Δ_p), from which the module is calculated (Fig. **1**). It is assumed p_{max} as a quasi-limit load, or equal to the doubled usable load, or at least greater than the usable load transmitted to the subgrade. In the case of subgrade of main lines for increased speed trains ($k_v = 2.0$) and axles pressure 225 kN, load on the track should be adopted around 0.165 MPa [8], [9], and $p_{max} = 0.35$ MPa, whereas the interval $\Delta_p = 0.10 \div 0.25$ MPa for the protective layer or $p_{max} = 0.25$ MPa and $\Delta_p = 0.05 \div 0{,}15$ MPa for the subgrade under this layer. For high-speed trains ($k_v > 2{,}0$) will be appropriate larger values of p_{max} and the interval Δ_p [8], [9].



1. Plots of subsidence of test plate and the method of their elaboration [7]

When checking the subgrade works are determined values of the modules of primary and secondary deformation. The value of the secondary module (1) is compared with the required E_{min} (tab. 1) [4]. The following condition should be fulfilled:

$$E'' \geq E_{min} \quad (2)$$

It is also determined the quotient of the two modules called deformation index:

$$I_o = \frac{E''}{E'} \quad (3)$$

This index, in fact, is the quotient of ground subsidence in a representative range of test load:

$$I_o = \frac{\Delta_{y'}}{\Delta_{y''}} \quad (4)$$

Tab. 1. Minimum values of deformation modulus of subgrade measured in trackway [4]

Speed v_{max} [km/h]	Transport intensity T [Tg/year]			
	$T \geq 25$	$10 \leq T < 25$	$3 \leq T < 10$	$T < 3$
$200 < v_{max} \leq 250$	120 (80)	120 (80)	120 (80)	110 (70)
$160 < v_{max} \leq 200$	120 (80)	120 (70)	110 (60)	100 (55)
$120 < v_{max} \leq 160$	120 (70)	110 (60)	100 (50)	90 (45)
$80 < v_{max} \leq 120$	110 (60)	100 (55)	90 (45)	80 (40)
$v_{max} \leq 80$	100 (50)	90 (45)	80 (40)	80 (40)

Explanations:
- the modules before the parentheses are required values for newly built and extension subgrade, as well as subgrade adapted(modernized) to speed v_{max} > 160 km/h,
- in the case of adaptation of subgrade for speed not exceeding 160 km/h, it should take the modules as for the newly built subgrade and treat them as a design (calculation) ones, not required (as required values it is adopted in such cases, the modules not smaller than those for the exploitation line, taking into account the possibility of obtaining these modules in water-soil conditions occurring on a given line);

- the modules in parentheses are the values required for the subgrade in exploitation lines; these values should be used when assessing the need to strengthen the railways and the design of their repairs.

The deformation index is characterized by thickening soil subgrade and strengthening layers, and should remain within specified limits [1], [6]. Standard [1], [6] and regulations [4] lay down specific requirements for the values of density (I_s) and deformation (I_0) indexes, which should be applied in assessing reconstruction of modernized subgrade.
According to the standards for excavation works of automobile roads [6], the assessment of density is made on the basis of the density index I_s. Alternatively, soil compaction, especially containing stones, can be evaluated on the basis of the deformation index I_0, whose value depends on the expected value of the density index and the type of soil assessed (Fig. 2), and should not be greater than:
for gravel, sand and gravel sand: 2.2 at the required value $I_s \geq 1.0$ and 2.5 at the required value $I_s < 1.0$,

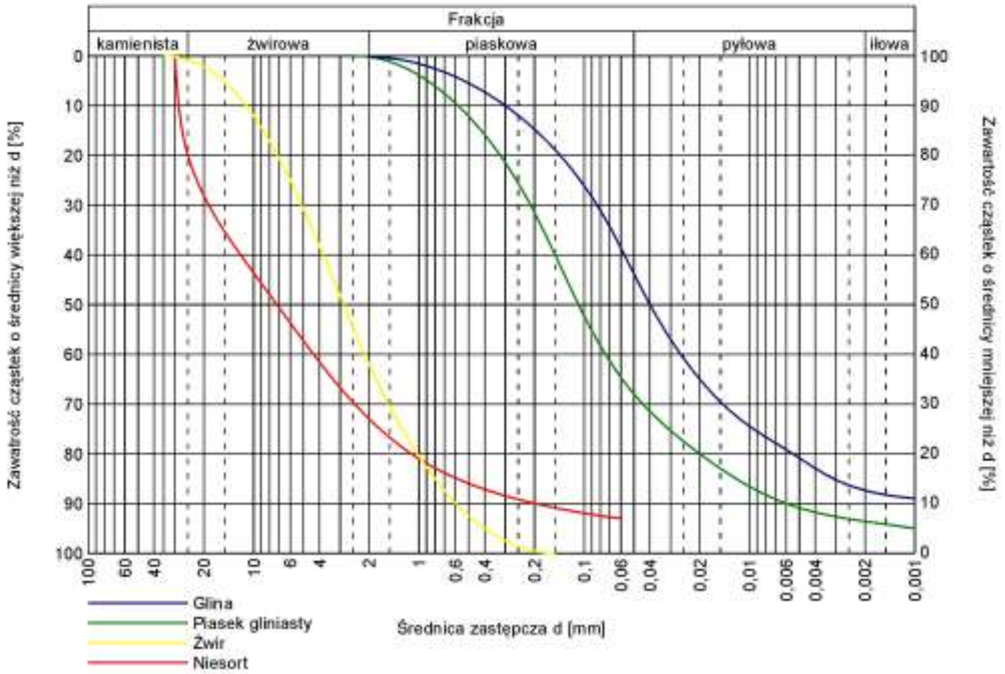
- for fine-grained soil with homogenous particle size (dust, clay, silty clay, concise clay and loam) – 2.0,
- for multigrain grounds (clayey gravels, clay gravel sands, sandy dust, sand, clay, sandy clay, sandy concise clay) – 3.0,
- for overhead stone and rubble – 4.0.

According to the standard for earth works on subgrade [1], density of grounds should comply with the conditions specified in Table 2. However, it is permissible to replace it by checking the value of deformation index, which should not be greater than 2.2. The required density of ground according to the regulations [4] is given in Table 3. The legislation also introduced three intervals of the state of soil compaction to assess the density index on the basis of the known values of the deformation index (Fig. 3). The boundaries of the intervals of the density state define equations:

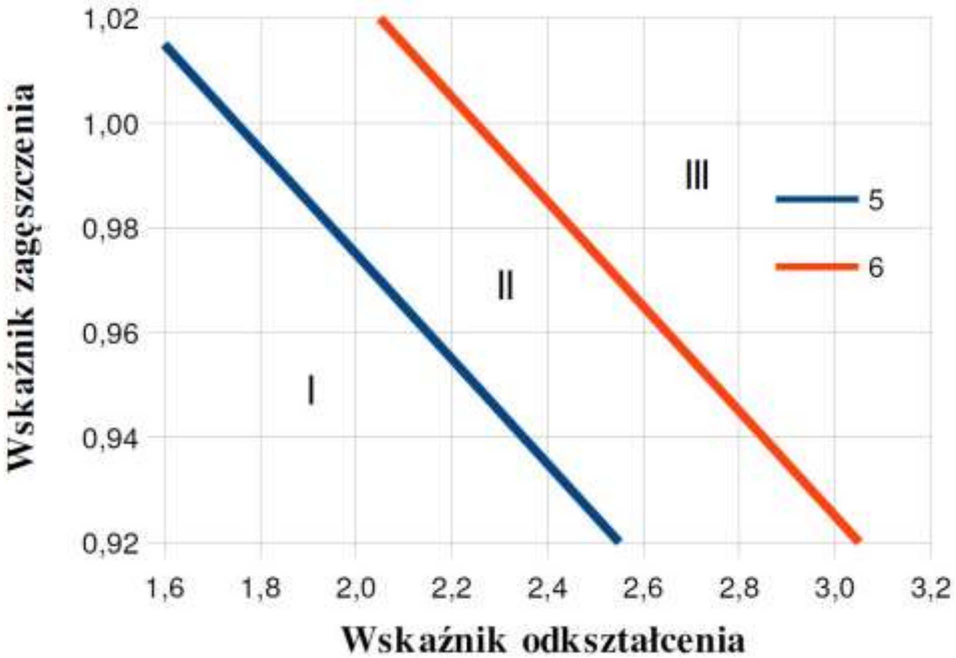
$$I_s = 1.175 - 0.1 \cdot I_0 \quad (5)$$

$$I_s = 1.225 - 0.1 \cdot I_0 \quad (6)$$

The method of assessment of soil compaction presented in the regulations [4], allows the assessment of subgrade compaction in the full range of the expected value of the density index. This value according to the equations (5) and (6) is independent of the type of subgrade soil, for which the state of compaction is evaluated. For the deformation index for value 2.2, the density index value equal to 0.96 is obtained from the equation (5), and equal to 1.01 from the equation (6), which is not in accordance with the regulations of standards [1], [6].



2. Granulation curves of different types of grounds and unsorted stone [7]



3. Evaluation of subgrade compaction based on the value of the deformation index according to the regulations of [4]; I - good density; II - doubtful density, III - insufficient density

Tab. 2. Required indices of subgrade compaction in main and primary lines [1]

Element of subgrade	Method comparing particular results of measurements	Statistical method	
	Density index	Mean density index	Variation coefficient [%]
Protected layer	≥ 1.00	≥ 1.00	≤ 2.0
Embankment body	≥ 0.95	≥ 0.95	≤ 2.5
Cut-off layer	≥ 0.95	≥ 0.95	≤ 2.5
Filter material for drainage facilities	≥ 0.92	≥ 0.92	≤ 2.5

Tab. 3. The minimum values of the density index for embankments [4]

Element of subgrade	Part of subgrade		Depth of railway [m]	I_S	
Embankment	upper		≤ 0.2	Unenriched mineral aggregates	
				≥ 1.03 [1)] ≥ 0.97 [2)]	
				Non-cohesive grounds	Cohesive grounds
				≥ 1.00	≥ 0.97 ≥ 1.00 [3)]
			0.2 do 2.0	≥ 1.00	≥ 0.97 ≥ 1.00 [3)]
	bottom	h ≤ 6.0	> 2.0	≥ 0.95	≥ 0,92
		h > 6.0			≥ 0,95
	substrate to 0.5 m from surface	h ≤ 2.0		≥ 1.00	≥ 0,97
		h > 2.0		≥ 0.95	≥ 0,92
Crosscut, a zero site	upper		≤ 0.2	≥ 1.03 [1)] ≥ 0.97 [2) 3)]	≥ 1.03 [1)] ≥ 0.97 [2) 3)]
			0.2 do 0.5	≥ 0.97	≥ 0.95

where h – the height of embankment, [1)] – build or extension of a new subgrade, [2)] – repair or modernization of the existing subgrade, [3)] – grounds stabilized by binders

A comparison of the required values of the deformation index in the standards [1] and [6], it is remarkable the lack of differentiation of requirements due to the nature of grounds and materials [1], [4] and the exclusion of the use of the deformation index to evaluation of soil compaction with moisture much less than optimal [6]. In similar standards, for both types of roads it is visible a significant contradiction, which is also present in subgrade projects - relying on the standard [1] and attempts to respect the value of 2.2 on building sites.

On the basis of the modules are determined values of secondary deformation modules of subgrade or protective layers or the system protective layer - subgrade and the corresponding sets of values of deformation indices. For individual sections of subgrade sets of values are obtained, which can be statistically examined in order to determine the quality (homogeneity), deformability and compactness of subgrade, as a measure of quality of works. [8], [9]:

$$w_E = \frac{\sigma_E}{\overline{E}''} \quad (7)$$

where: σ_E - standard deviation of modules of the secondary deformation of subgrade, $\overline{E}''$ - average value of the secondary deformation module of subgrade.

Similarly, statistical analysis may be performed on values of deformation indices:

$$w_{I_0} = \frac{\sigma_{I_0}}{\overline{I_0}} \quad (8)$$

where: σ_{I_0} - standard deviation of deformation indices of subgrade, $\overline{I_0}$ - average value of the deformation index of subgrade.

An example of statistical analysis of reception research of the selected section of the E30 line is included in Table 4.

Tab. 4. Summary of the results obtained during the modernization of the section of the line E-30 [2]

	Track no 1			Track no 2		
	E_1 [MPa]	E_2 [MPa]	I_0 [-]	E_1 [MPa]	E_2 [MPa]	I_0 [-]
Number	46			45		
Minimum	22	109	1.97	24	108	1.71
Maximum	64	143	5.00	72	155	4.54
Mean	47.85	123.02	2.67	40.55	121.40	3.27
Standard deviation	8.92	8.25	0.58	14.57	12.49	0.82
Variability coefficient	0.19	0.07	0.22	0.36	0.10	0.25

Stress and settlement of subgrade under the plate

Measured values of secondary deformation modules of the subgrade are used to assess the suitability of reinforced subgrade with the request of the condition (2), and at the same time the calculated values of strain, which should meet certain requirements [1], [4] or better [6]. It results in the enlargement of significance of test load with the VSS plate, as a basic condition for the study determining the course and acceptance of works and the plate VSS ranks as the main tool for testing parameters describing quality of subgrade works. For these reasons, the analysis of co-operation loading plate with medium controlled by its application is justified. The analysis was performed defining the stress and deformation states (settlement) in the subgrade under the plate, remaining under load corresponding to the limit values of sampled load Δ_p = 0.10÷0.25 MPa and the greatest load p_{max} = 0.35 MPa. For the analysis, we assumed a simple case of subgrade reinforced with a single protective layer of gravel with a thickness of 0.3 m, built on the existing subgrade of fine sand in the concentrated state. Geotechnical (physical and mechanical) parameters of subgrade soil were taken from the literature [10].

Calculations of stress were carried out according to the standard [5] and [10] by treatment the subgrade with a protective layer as a half-space bounded from the top by a new track, extending infinitely deep. In determining the stress from external loads it was assumed that the subgrade is elastic (linear-deformable), isotropic and homogeneous. In the analysis, we considered the load from soil weight. The value of stress $\sigma_{\gamma z}$ was determined from the equation:

$$\sigma_{\gamma z} = \sum_{i=1}^{n} \gamma_i \cdot h_i \quad (9)$$

where: γ_i – volume weight of soil in each layer i, h_i – the thickness of the individual layers i.

Stresses from test load with test plate were determined with the assumption that the plate is perfectly rigid, using the formula:

$$\sigma_{zq} = \eta \cdot q \quad (10)$$

where: η – coefficient of stress distribution by nomogram [5], q – unit pressure of the plate.

The values of coefficient of the vertical stress distribution η loaded by the circular rigid plate with the diameter R can be determined from the formula [5]:

$$\eta = f(z, R) \quad (11)$$

where: R – radius of the circular area, z – the depth in which stress is determined.

In the calculations of subsidence, ground subgrade was adopted as a homogeneous linear-elastic half-space. We also included the assumed examples layering of subgrade under the plate. Values of subsidence were calculated using values of stress occurring in the middle of layer thickness. The settlements so calculated, for all separated layers, were summed to a depth of:

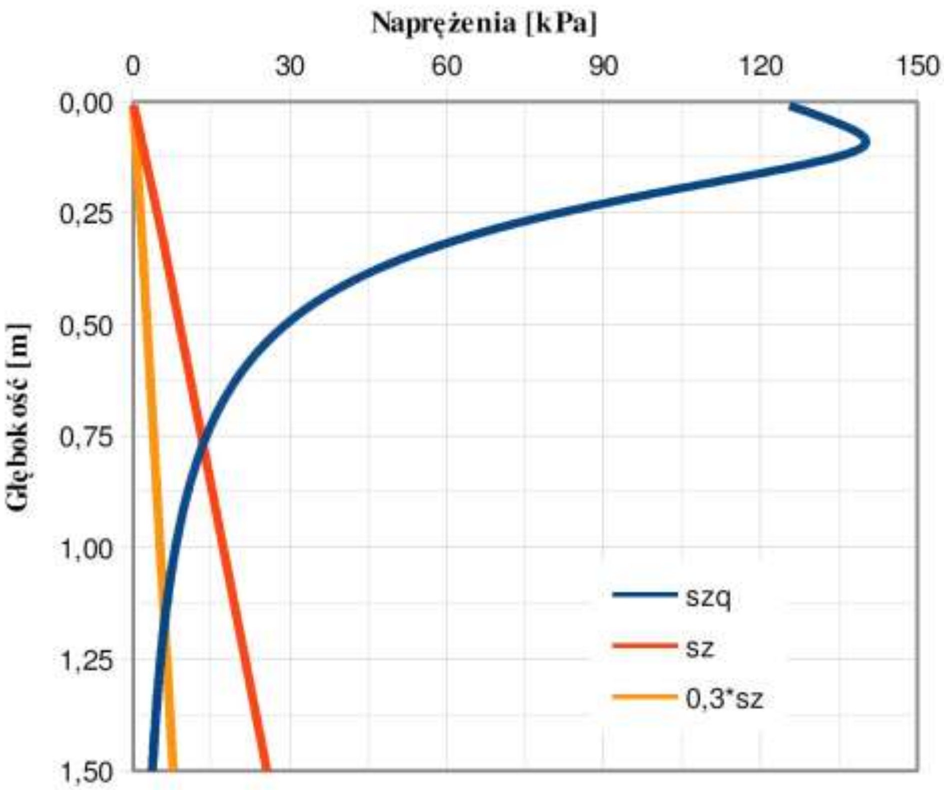
$$\sigma_{z_{\max} q} \leq 0.3 \cdot \sigma_{z_{\max} \gamma} \quad (12)$$

We included geotechnical parameters corresponding to the subgrade state in the first load by the test plate with a diameter of 0.3 m, i.e. the overall deformation modules E_0 and calculated on the basis the edometric modules of initial compressibility M_0. The results of calculations of the subgrade subsidence with the protective layer are summarized in Table 5.

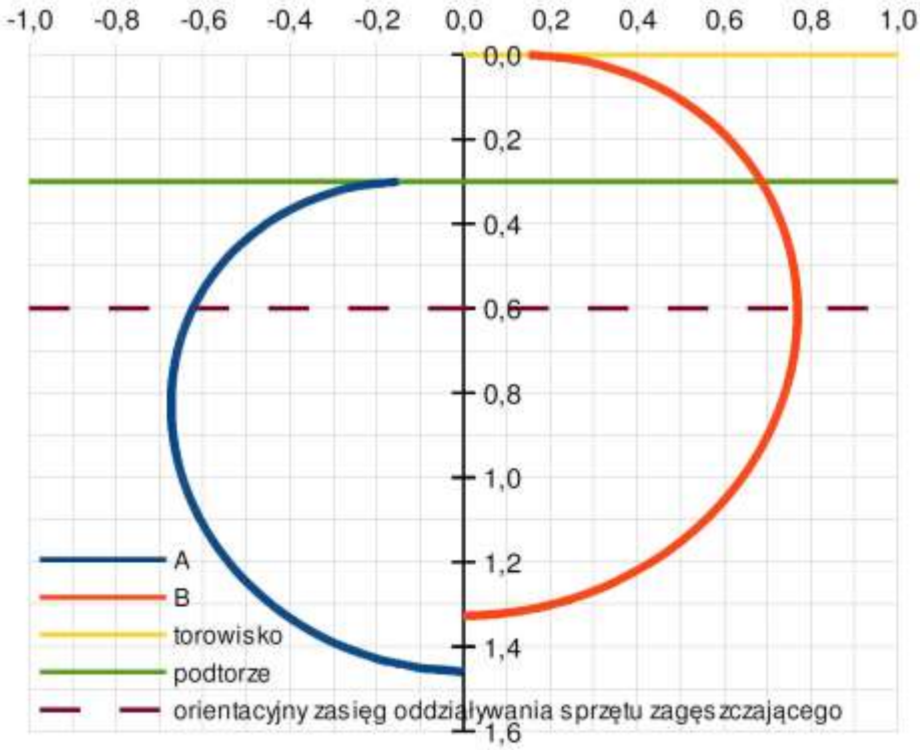
Tab. 5. Values of subgrade settlement with a protective layer in considered cases of loading

Subgrade parameters			Load [MPa]					
Element of subgrade	Weight	Module	0.10		0.25		0.35	
			Settlement					
	[kN/m^3]	[MPa]	[mm]	[%]	[mm]	[%]	[mm]	[%]
Railway	-	E_{ekw} = 142	0.120	100.0	0.323	100.0	0.465	100.0
Protected layer	18.5	E_0 = 200	0.062	51.1	0.154	47.7	0.215	46.3
Subgrade	16.7	E_g = 78	0.059	48.9	0.169	52.3	0.249	53.7

Values of stresses in the subgrade (Fig. 4) indicate that the loading plate affects its own subgrade to a depth depending on the type and condition of the soil in the medium and the used pressure. Generally, one can assume that this interaction during the normal test of the subgrade with a protective layer reaches a depth of about 1.3 m from the track, which is about 4D (Fig. **5**, the curve B). In the case of performing measurements on the substrate of protective layer, the depth of the impact plate is approximately 1.15 m, or about 1.45 m from the track (Fig. 5, the curve A). Therefore, it can be concluded that the settlement (Tab. 5) determine the values of deformation indices, not only the same layer, but also the subgrade under the layer, and in the general case, the stratified subgrade or ground containing an addition of other grounds. In the calculation example, only about 50% of the total subsidence generated during the test load of the subgrade with the plate, results from the deformation of the protective layer. The remaining portion results from the settling soil subgrade (Tab. 5). Considering values of the deformation index specified for different types of soil in the document [6] is to be expected as a result of different values of the subgrade control tests, however, not corresponding the values as indicated in [6]. Additional circumstance are very compressible geotextiles in the construction of subgrade, which increase values of settlements and also change the value of the deformation index on disadvantageous for evaluation of the subgrade compaction.



4. The stress state in the subgrade of fine sand with a protective layer of gravel. The load plate is 0.35 MPa (Tab. 5).

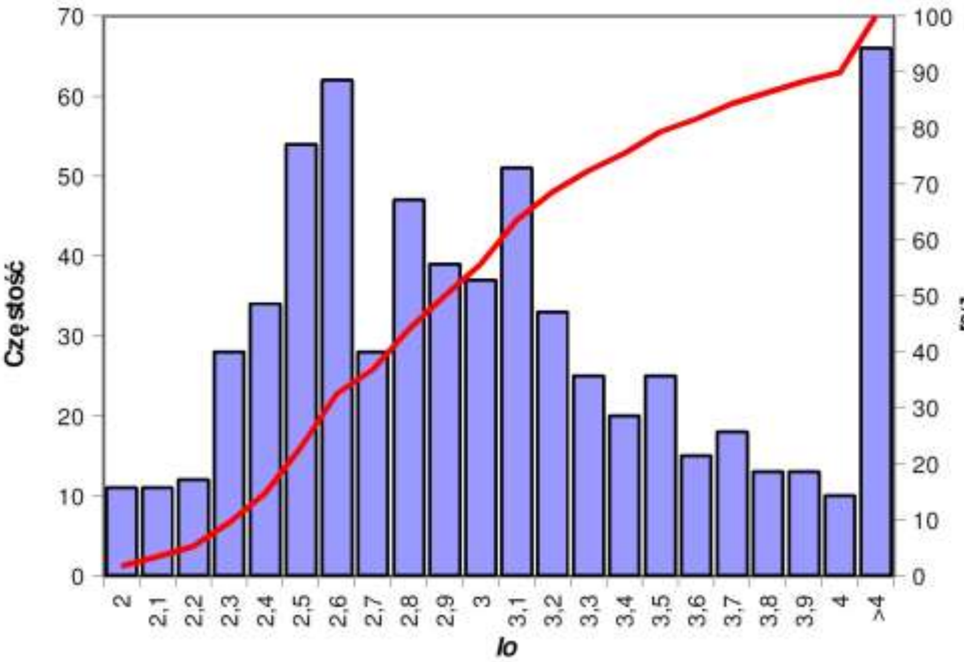


5. Extent of impact of uniformly loaded circular plate in the middle of subgrade of medium-sized sand (A) and medium-sized sand with a protective layer having a thickness of 0.3 m made of gravel (B); load plate is 0.25 MPa (A) and 0.35 MPa (B). The depth was measured from the track [3].

Concluding remarks

Taking into account the current required minimum modulus of subgrade deformation measured on the trackway (Table. 1), with the distinction between the computing and required values, it should be noted that the greatest density of ground and materials (the largest value of the density index) will correspond to the measured values of deformation modules consistent with the calculation values. The density will be accordingly lower (density index value) when the lower value of the modules is required. Smaller density must be accepted in such control concept and acceptance of works. It means that then it should not be used the method of determining the density state according to the state of deformation index, including the dependence of both indices according to the standards.

In assessing the significance of research of deformation modules and indices it should be considered that the strength of the protective layer according to the design is calculated taking into account the strength of the subgrade at the weakest (most difficult) site of the section with the constant layer thickness. As a result of this, in other sites of the subgrade along the length of the layer, values of deformation modules and indices may have other values than those required by the standards and regulations. Similarly, on the length of the layer section can occur sites in which the values of deformation modules and indices show weaker strength of layers, because the control of properties of the subgrade before the project is carried out in sites far distant from one another. Properties of ground may be less favourable and the protective layer will be in these sites too weak. Thus, as the results of the research of deformation modules and indices, it should be taken into account the actual measured values, without their "rounding" to the required standards and regulations. Sets of results from geotechnical studies at all stages of remodelling, design and construction should contain a naturally diverse values (Fig. 6), which should be approved in the controls and approvals of works. The deformation modules, and therefore density should be the last parameters determined in the approvals of works.



6. Distribution of values of deformation index for the system protective layer - subgrade and the cumulative distribution of deformation index for the set of sample values of deformation indices for several rebuilt sections of the lines E-20 and E-30 [7], [2]

Conclusions

1. The index of substructure deformation does not allow for an accurate assessment of the index of soil compaction and materials of real railway subgrade.
2. Reliability of evaluation of the real density of subgrade based on the deformation index could be increased by analysing in each research site a geotechnical profile and the effect of geotextile, regarding the actual depth of the impact of the test plate, i.e. the depth 4*D* from track railway.
3. During verification tests of the modernized subgrade the deformation index was most commonly in the interval I_0 = 2,6÷3,1; it can be assumed that in these limits, the subgrade is in the required state of density.
4. The application of ordinary geotextiles in the upper zone of the subgrade makes definitely difficult to assess the density of subgrade based on research results of its deformability.

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