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Designing of railway track subgrade with reference to the requirements of the Eurocode 7 standard

Abstract. In this paper, the Eurocode 7 as a collection of requirements and general recommendations for geotechnical designing from the perspective of railway superstructures and track operation is discussed. The problems touched upon includes fundamentals of design of geoengineering structures, Eurocode 7 provisions applicable to increasing of the load bearing capacity of a subgrade and the Eurocode 7 recommendations concerning direct foundations with reference to a railway track structure. Special emphasis has been put on the methods applied to calculate settlement of direct foundations and the options of adapting them to the track design. Furthermore, selected opinions and comments on Eurocode 7 provided in geotechnical publications are discussed.

Key words: railway track, subgrade designing, Eurocode 7

1. Introduction

According to contemporary design solutions of a railway track superstructure[1], being adapted to match the traffic conditions ensuring high comfort and driving speed equivalent to Western European railways, one should provide for the necessary and close cooperation between the track and the subgrade ("the level layer of rock or earth upon which the foundation of a road or railway is laid"[2]). Therefore, it is of utmost importance that the processes of superstructure

[1] See, for example, H. Petrovski, *Design Paradigms: Case Histories of Error and Judgment in Engineering*, Cambridge University Press, Cambridge 1994; J. Leong, *Development of a Limit State Design Methodology for Railway Track*, 2007, http://eprints.qut.edu.au/16565/1/Jeffrey_Leong_Thesis.pdf [15.02.2013].

[2] http://www.thefreedictionary.com/subgrade [15.02.2013].

design and track operation should be adjusted to the current requirements of the applicable standards, ordinances and European regulations like Eurocode 7. The Eurocode 7 will be used in this paper for analysinf the design of railway track subgrade[3]. Special attention is given to how subgrades of low load bearing capacity function, namely those which require strengthening.

The aim of this article is to provide an overview of problems related to railway track design in Poland against the background of European regulations, as provided in Eurocode 7, and the guidelines prepared in Poland drawing from the European code. First, regulation on establishing geotechnical conditions for the foundation of structures is discussed. Then, the Eurocode 7 as a set of requirements and general recommendations for geotechnical design is elaborated, and a calculation of direct foundation settlement with reference to a railroad design is provided. Discussion of the issue is relevant, as standardization of geotechnical design is crucial for the long-term operation of railroad tracks and diffusion of technological know-how. However, the complexity of Eurocodes raises the question whether it should rather be applied to large scale design with low risk and few uncertainties, as non-standard design also requires non-standard solutions.

2. Regulation on establishing geotechnical conditions for the foundation of structures

Specialists in the field of geoengineering are obliged to apply to the Regulation of the Minister of Transport, Construction and Maritime Economy of 25th April 2012 on establishing geotechnical conditions for foundation of structures[4] referring to the provisions of Eurocode 7[5]. Regulation provides detailed principles to be fulfilled when establishing geotechnical conditions for foundation of structures, including[6]:

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[3] PN-EN 1997-1: 2008. Eurocode 7. Projektowanie geotechniczne. Część 1: Zasady ogólne [Geotechnical design. Part 1: General rules]; PN-EN 1997-2: 2007. Eurocode 7. Projektowanie geotechniczne. Część 2: Rozpoznanie i badanie podłoża gruntowego [Geotechnical design. Part 2: Ground investigation and testing].

[4] Rozporządzenie Ministra Transportu, Budownictwa i Gospodarki Morskiej z dnia 25 kwietnia 2012 r. w sprawie ustalania geotechnicznych warunków posadawiania obiektów budowlanych, Dz.U. poz. 463 [Regulation of the Minister of Transport, Construction and Maritime Economy of 25th April 2012 on establishing geotechnical conditions for foundation of structures, Official Journal of Laws, item 463].

[5] PN-EN 1997-1: 2008, op. cit.; PN-EN 1997-2: 2007, op. cit.

[6] Rozporządzenie Ministra Transportu, Budownictwa i Gospodarki Morskiej z dnia 25 kwietnia 2012 r. w sprawie ustalania geotechnicznych warunków posadawiania obiektów budowlanych, Dz.U. poz. 463.

– estimation of significant subgrade properties for the sake of service safety, such as load bearing capacity, displacement (settlement) and stability,

– choice of the method to improve the subgrade and secure earth structures against landslides,

– determination of quality and conditions of interaction between the structure (railway track) and the subgrade at the stage of construction and operation as well as the impact exerted by the structure (e.g., dynamic load) on the surrounding.

Regarding the Regulation, a distinction has been made between three types of soil conditions depending on the degree of their complexity, namely simple, complex and complicated conditions.

Considering the railway track subgrade, often composed of discontinuous soils, inhomogeneous along the entire railway route, genetically diverse and comprising mineral soils as well as locally organic soils of low load bearing capacity, such soil conditions should be classified as complex. Whereas in the case of the track substructure developed in areas exposed to mining damage, where discontinuous rock mass formations may occur, soil conditions are considered to be complicated.

Regulation imposes an obligation to establish a geotechnical opinion for all geotechnical structures. Based on the opinion, a geotechnical category of the given structure is defined.

A railroad may be classified under the first, second or third category of geotechnical structures. The first category includes right-of-way structures (namely motor roads and railroads) running in cuts of the depth ≤ 1.2 m and on embankments of a height ≤ 3.0 m. The second geotechnical category comprises structures founded under simple and complex soil conditions, which require quantitative and qualitative assessment of geotechnical data as well as their analysis. Bearing in mind the fact that railway lines are investments which may exert a considerable environmental impact (bringing up the issue of natural compensation[7]), which are often built under complicated soil conditions and may sometimes have the significance of critical infrastructural items, they should also be classified under the third geotechnical category.

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[7] M. Drusa, "Oporné konštrukcie dopravných stavieb", in: *Stavební konstrukce z pohledu geotechniky: Česko-slovenská konference, Brno, 11-12 December 2008*, Brno 2008, pp. 41-44; M. Drusa, "Vhodnost' pouzitia klasickych a novych sanacnych metod pri zabezpecovani stability svahov", *Projekt a stavba* 2001, No. 4, pp. 8, 9, 14; M. Drusa, J. Benda, "Ochrana svahov strmych nasypov geobunkovou strukturou", in: *Geosyntetika v stavebnictve*, Žilina 2007, pp. 117-122; M. Drusa, B. Prelovsky, "Problemy pri navrhovani a realizacii vysokych nasypov na neunosnom podlozi", in: *Geosyntetika v stavebnictve*, Žilina 2007, pp. 123-131; W. Kozłowski, A. Surowiecki, "Solutions Related to Environmental Conditions in the Process of the Modernization of Main Railway Lines", *Problemy Kolejnictwa* 2011, Vol. 152, pp. 251-265; A. Surowiecki, "Modernizacja konstrukcji dróg szynowych", in: A. Surowiecki, *Badania modelowe i eksploatacyjne*, Wyd. Wyższej Szkoły Oficerskiej Wojsk Lądowych we Wrocławiu, Wrocław 2012.

Depending on how the given structure has been classified under one of the three geotechnical categories, the applicable scope of geotechnical soil tests has been specified in Regulation. For instance, earth structures (road or railway embankments) classified under the second and third geotechnical category require (besides basic tests mandatory for all first category structures) supplementary tests whose scope should depend on the projected degree of complexity of soil conditions.

As regards the subgrade improvement for structures of the second and third geotechnical category, it has been recommended in Regulation that additional tests should be conducted in order to determine the potential outcomes of the soil improvement and estimate the technical parameters of the material used to improve the soil. As for the second and third geotechnical category structures, Regulation stipulates an additional obligation to develop the subgrade testing documentation and geotechnical plans and specifications. For the structures of the third geotechnical category and whenever complex soil conditions have been diagnosed, there is one additional obligation, namely to draw up geological engineering documentation in accordance with the provisions of act[8].

3. Eurocode 7 as a set of requirements and general recommendations for geotechnical design[9]

The fundamentals of design of geoengineering structures based on the Eurocode 7 are discussed below. One of the requirements specific to Eurocode 7 is making the scope and type of subgrade testing, necessary to conduct verifying calculations and the obligatory structure workmanship inspection, dependent on the degree of the structure's geotechnical category. Geotechnical categories of structures characterise the degree of difficulty to perform an investment task and they have been defined in Regulation[10].

Eurocode 7 provides detailed contents in the scope of fundamentals of geotechnical design. They include[11]:

1. Design requirements (21 items in total, including obligatory verification whether or not any applicable threshold state is to be exceeded for every geotechnical design situation, and specification of methods recommended to verify the threshold states).

[8] Ustawa z dnia 9 czerwca 2011 r. Prawo geologiczne i górnicze, Dz.U. nr 163, poz. 981 [Act of 9th June 2011 – Geological and Mining Law, Official Journal of Laws No. 163, item 981].

[9] PN-EN 1997-1: 2008, op. cit.; PN-EN 1997-2: 2007, op. cit.

[10] A. Surowiecki, op. cit.

[11] PN-EN 1997-1: 2008, op. cit.; PN-EN 1997-2: 2007, op. cit.

2. List of design situations to be analysed (once they have been qualified as short-term and long-term) entailing consequences of the impact of time and the environment on the strength and material properties of the structure, e.g., local soil fretting zones in the embankment which have occurred due to animal activity.

3. Assessment of the relevance of environmental conditions for the durability of the materials used (what matters as regards geosynthetics used for improving purposes is the effects of ageing resulting from chemical degradation).

4. Geotechnical design guidelines based on calculations, including a detailed specification of elements to be taken into consideration. As regards railroads, it is recommended that special attention should be paid to the impacts which may result from displacements caused by numerous factors including kinematic changes taking place in the subgrade. Moreover, it is reasonable to entail the mutual interaction between the track structure and the soil subgrade as well as the impact of duration time of the influence exerted on the physical and mechanical properties of the subgrade soils, including particularly the course of the filtration process and compressibility of fine-grained soils (according to PN-ISO 14688-1: 2006[12], the category of fine-grained soil comprises cohesive soil of grain diameter ≤ 0.063 mm, i.e., silts, clays and ashes).

Furthermore, Eurocode 7 also contains:

a) requirements pertaining to the choice of characteristic values and representative reactions,

b) requirements pertaining to the choice of characteristic values of geotechnical parameters (for each case, the most unfavourable combination of what is referred to as the lower and the upper values of independent parameters must be applied),

c) principles of assuming characteristic values of geometrical data (ground level, underground or surface water horizon),

d) methods applied to determine design values for reactions, geotechnical parameters and geometrical data as well as design strengths of structural materials (e.g. strengthening layers),

e) principles of verification of exceeding the following threshold states of load bearing capacity:

– EQU (balance loss in the structure or subgrade, where the objects are treated as rigid bodies, disregarding the relevance of strength of structural materials and the subgrade),

– STR (internal failure of the structure or its components, or deformation exceeding the permissible value, assuming crucial relevance of the strength of materials in ensuring the structure's load bearing capacity),

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[12] M. Drusa, M. Moravčik, *Foundation Structures*, University of Žilina, Faculty of Civil Engineering, Žilina 2008; M. Drusa, "Oporne konstrukcie dopravnych stavieb", op. cit.; M. Drusa, "Vhodnost' pouzitia klasickych...", op. cit.; PN-EN 1997-1: 2008, op. cit.

– GEO (state of subgrade failure or deformation exceeding the permissible value, assuming the ground strength to be a factor decisive for ensuring the load bearing capacity). Eurocode 7 states that the GEO state is basically reliable enough when applied in dimensioning of structural elements of foundations. The foregoing may be referred to a railway track as a foundation set upon a soil subgrade,

– UPL (vertical balance loss, being a stability loss in the structure or the subgrade, caused by vertical impact or water filtration in the structure causing lift or pressure),

– HYD (internal erosion or piping in the structure's subgrade due to hydraulic gradient),

f) principles of verification of not exceeding threshold states of operational use: in the subgrade and in the given structural component (for a railway track, this would be the track grate structure or the layer of ballast under sleepers, or the track subgrade).

Eurocode 7 also includes provisions on increasing the subgrade load bearing capacity[13]. Eurocode 7 recommends that geotechnical studies should be conducted before choosing the method for the subgrade improvement or strengthening. The purpose of such studies is to obtain data enabling the 'initial' soil conditions to be diagnosed.

As for planning the method for the subgrade strengthening according to Eurocode 7, it has been suggested that the following should be taken into account (subject to the 'if needed' clause):

– physical and mechanical properties of the subsoil subgrade or the embankment material and thickness of these layers,

– underground water flow directions and runoff pressure,

– subgrade improvement effect (understood as a permanent effect for a railroad),

– dependence between the method of subgrade strengthening and the sequence of technological operations conducted at the construction site with regard to the deformations projected (no such problem occurs for a railroad, since the travel of machines laying track rails contributes to compacting of the strengthened subgrade),

– negative environmental impact. The preparation and assembly of protective layers classified as physical and chemical improvements[14] (e.g., soil improvement with cement, lime, liquid bitumen, urea resins, cement dust, lignosulphonates) may lead to contamination of the adjacent areas with toxic compounds or

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[13] PN-EN 1997-1: 2008, op. cit.; PN-EN 1997-2: 2007, op. cit.

[14] M. Drusa, M. Moravčik, op. cit.; M. Drusa, "Oporne konstrukcie dopravnych stavieb", op. cit.; M. Drusa, "Vhodnost' pouzitia klasickych...", op. cit.; M. Drusa, J. Benda, op. cit.; M. Drusa, B. Prelovsky, op. cit.; PN-EN 1997-1: 2008, op. cit.; PN-EN 1997-2: 2007, op. cit.

initiate a change in the underground water horizon. Therefore, dedicated official proceedings should be conducted according to special procedures comprising an analysis and assessment of all aspects of impact for such investment types[15]. The proceedings in question end with issuance of a decision on environmental conditions for the investment performance approval specifying all sorts of aspects including the measures to be undertaken in order to minimise the negative environmental impact of the project. Those measures are related to maintenance of the standards defined in the environmental protection law[16],

– process of long-term ageing of geosynthetics the strengthening inserts are made of.

What has also been stressed in Eurocode 7 is the necessity to verify the stability of the subgrade strengthening elements. This verification should consist in estimation of the desirable changes in the soil properties assumed to be affected by the strengthening method applied.

Eurocode 7 also provides recommendations for direct foundations[17]. Direct foundations include isolated footings, continuous footings and slab foundations. A railway track set on the ground level in the form of a conventional (track grate with broken stone ballast) or unconventional (without ballast, e.g., track grate founded on concrete or reinforced concrete slabs) superstructure could be regarded as direct foundation as well. In such a case, it would be reasonable to apply the provisions of Eurocode 7 which comprise the following aspects: examination of threshold states for load bearing capacity and operational use.

Verification of the load bearing capacity threshold state comprises: overall structure stability (including on an embankment or near an embankment or a retaining wall), subgrade load bearing capacity, sliding resistance along the structure base. The problem of sliding resistance occurs when the operating load is not applied perpendicularly to the structure foundation footing. For a railroad, such a situation takes place, for instance, during the vehicle braking, when the horizontal forces which occur act towards the longitudinal track axis, and in a track of insufficient structural stability, horizontal forces H acting perpendicularly to the longitudinal track axis are pointed outside the track. Forces H may reach the values of ca. 0.4 P, where P is the vehicle wheel load on the rail, and in accordance with the UIC standard, it equals $P = 110.5$ kN.

The threshold load bearing capacity state may occur due to vertical and horizontal differences in the displacement of foundations (against the railway track, the said displacement state may occur as a consequence of the subgrade instability).

[15] PN-EN 1997-1: 2008, op. cit.; PN-EN 1997-2: 2007, op. cit.

[16] W. Kozłowski, A. Surowiecki, op. cit.; A. Surowiecki, op. cit.

[17] PN-EN 1997-1: 2008, op. cit.; PN-EN 1997-2: 2007, op. cit.

For threshold states of the second group, Eurocode 7 provides a number of significant remarks which may address the track-subgrade structural system:

– calculation of settlements (vertical displacements) taking place in plastic cohesive soils is necessary,

– settlement calculation results should be treated as approximate only,

– while calculating increases of loads in the subgrade layers and their impact on the phenomenon of soil compressibility, it is recommended that the influence of adjacent structures should be taken into account (in the case of a railroad, an adjacent structure may be another track in a two-track line).

As for the settlement calculations, it has been recommended in Eurocode 7 that the following three components should be taken in to consideration: instantaneous settlement (s_0) due to non-dilatational strain and volume decrease, settlement due to consolidation (s_1) and s_2, i.e., settlement as an effect of secondary consolidation (creep). It is also recommended that known classical methods of settlement calculation should be applied. Examples of such methods with reference to components s_0 and s_1 have been provided in the applicable annex.

The active subgrade depth, where the structure's impact on the soil deformation ends, is to be assumed at the depth where the effective vertical stress caused by the operating load equals 20% of the effective primary stress generated by the weight of the soil overlay.

While estimating settlement differences, besides the distribution of loads, one should also take the subgrade variability (inhomogeneity) into consideration. Eurocode 7 emphasises the problem of the structure rigidity from the perspective of calculation of settlement differences stating that, without having entailed the rigidity factor, the settlement calculation results are overstated. Therefore, it is assumed that an analysis of the structure and subgrade cooperation should be conducted.

Eurocode 7 contains general principles for design of direct foundation structures and subgrade preparation. For a railway track, considered as a direct foundation, the following remarks are of importance:

– the thrust of a rigid foundation on the subgrade may be assumed as linearly distributed,

– for a flexible foundation, the distribution of vertical thrusts at the contact with the subgrade may be estimated assuming a model of foundation as a beam or a slab set upon a deformable half space or upon a flexible single-parameter footing (of the Winkler type),

– it can be argued that the methods defined in Eurocode 7 to determine total settlement and settlement differences for an entire structure are not absolutely accurate, since in many cases, the subgrade reaction models are inappropriate for the calculations provided. Therefore, it has been recommended that more exact methods (e.g., the finite element method) should be applied, particularly when the mutual subgrade and structure reaction is decisive for the functioning of the given facility. Such a situation is certainly the case of railways, where the foundation structure is the track grate, as it is referred to, founded on a layered subgrade (the contemporary subgrade pattern includes: the ballast layer, the protective layer or layers and the soil layer known as the track substructure).

4. Calculation of direct foundation settlement with reference to railroad design

According to Eurocode 7, it is allowed that the commonly applicable method specified in standard PN-81/B-03020[18] should be used, where the foundation is considered as perfectly flexible, whereas the distribution of loads in the subgrade does not depend on deformation modulus E and Poisson's ratio v.

In certain scientific papers, the direct foundation settlement estimation procedure defined in Eurocode 7 has been considered debatable[19]. Iwona Chmielewska et al. have shown[20] that, disregarding the foundation rigidity, by application of the corner point method in order to calculate stresses and settlements at the points located on the foundation edge or near the edge, causes considerable errors. The range of these errors is particularly important when the Δs settlement differences are also calculated at individual foundation points. One cannot question the relevance of the impact of the Δs parameter value on the degree of the railway track stability. It has been mentioned in the conclusions of the publication that settlements of a foundation perceived as rigid, affected by a service load of q [MPa], are more than a dozen per cent smaller than settlements of the foundation centre point where the rigidity factor has been disregarded. Hence, the error referred to in article is orienting the calculation results towards the structure safety.

Annex F to Eurocode 7 contains a description of two methods of settlement estimation:

1) summation of the subgrade layers' deformations,
2) simplified elastic medium method.

What has also been provided is the basic information on settlements under conditions free of underground water outflow, consolidation settlements and the settlement course in the function of time.

[18] PN-81/B-03020. Grunty budowlane. Posadowienie bezpośrednie budowli. Obliczenia statyczne i projektowe [Direct foundation of structures. Static calculations and designs].

[19] See e.g. I. Chmielewska, K. Dołżyk, Z. Szypcio, "Szacowanie osiadań fundamentów bezpośrednich", *Zeszyty Naukowe Politechniki Rzeszowskiej. Budownictwo i Inżynieria Środowiska* 2012, Vol. 59, No. 283(3/2012/IV), pp. 9-16.

[20] Ibidem.

The elastic medium method is based on application of the theory of elasticity which assumes a linear course of deformations in the function of load. In railway engineering, it is permissible that the subgrade should work in the elasticity area, and all the more, one should focus on the provisions of Eurocode. However, a subgrade is not always homogeneous, in which case Eurocode 7 recommends special caution. According to this standard, the total foundation settlement (regardless of the soil type) is expressed by the following formula:

$$s_{z,\,tot} = q \times b \times f_0 \times (E_{s,\,des})^{-1} \tag{1}$$

where:

q – vertical stress in contact between the foundation and the subgrade (subgrade thrust) [MPa],

b – foundation width (i.e., sleeper width in the case analysed) [m],

f_0 – dimensionless settlement factor,

$E_{s,\,des}$ – design elasticity modulus [value MPa].

Settlement factor f_0 is a multiple parameter function, and its value depends on the shape and dimensions of the foundation footing, changes to the ground rigidity (the ground is to be understood as the sleeper) depending on the depth, Poisson's ratio, distribution of thrusts of the foundation (sleeper), the point for which settlement is calculated and thickness of the compressible layer (i.e., the active track substructure layer). The active track substructure layer is set by depth z at which the $\sigma_{d,\,z}$ secondary stress from the track structure equals 30% of primary stresses $\sigma_{y,\,z}$[21].

According to theoretical considerations regarding a railway track superstructure, the distribution of subgrade (broken stone ballast) thrusts along the sleeper is to be assumed as uniform provided that the sleeper is perceived as a perfectly rigid bar. For an elastic sleeper and elastic ballast, however, the graph of vertical contact stresses is curvilinear and reaches its maximum values in sub-rail zones. The sleeper pressure on the ballast across the width of the sleeper cross-section is distributed non-uniformly (in a parabolic shape). The maximum of the thrust graph equals $\sigma_{v,\,max} = 1.6\ \sigma_{mean}$ (where σ_{mean} is mean thrust) and it occurs in the centre of the cross-section. Assuming the mean sleeper thrust on the ballast of $\sigma_{mean} = 0.3$ MPa, one obtains the maximum thrust of $\sigma_{v,\,max} = 1.6 \times 0.3 =$ $= 0.48$ MPa[22].

It is commonly known that a track grate is an assembly composed of two rail sets attached to transverse sleepers spaced in regular intervals. Consequently, the

[21] A. Surowiecki, op. cit.

[22] Ibidem.

zones of vertical stresses under the sleepers are combined below a certain depth (assumed as characteristic) under the sleeper, which typically is above 0.5 m. At depths slightly larger than the inter-sleeper clearance designated as a_0 (typically a_0 = 0.55-0.60 m), a pressure of uniform horizontal distribution acts.

As regards the design modulus of elasticity ($E_{s,\,des}$), Eurocode 7 provides the following: the value of $E_{s,\,des}$ under the conditions of water outflow in the ground can be estimated based on results of laboratory tests (of samples collected from the soil) or on-site tests.

Besides formula (1) derived from Eurocode 7, there is also a general form of the formula applied to calculate settlement of uniform elastic half space s_z[23]:

$$S_z = (1 - v^2) \times q \times B \times w_s \times (E_{elast})^{-1} \tag{2}$$

where:

w_s – dimensionless settlement factor depending on the quotient of *L/B* (*L* – longer side of the foundation, i.e., the railway sleeper [m]; *B* – sleeper width [m]),

v – dimensionless Poisson's ratio,

E_{elast} – modulus of elasticity [MPa].

Other symbols have been assumed following formula (1).

It is obvious that rigidity of the foundation (sleeper) and of the structure cooperating with the former (rails attached to the sleeper with fasteners) affect the settlement values for that sleeper. Foundation rigidity k_f can be calculated as follows:

$$k_f = E_e \times H^3 \times (E_{0,\,s} \times u_f^{\,3})^{-1} \tag{3}$$

where:

E_e – foundation's modulus of elasticity [MPa],

H – foundation height [m],

$E_{0,\,s}$ – subgrade's modulus of deformation [MPa],

U_f – foundation dimension corresponding to the direction of settlements analysed (basically along the sleeper) [m].

Settlement calculation for a rigid rectangular foundation ($s_{f,\,s}$) axially loaded with force *Q* (assuming elastic half space under the foundation) may be performed by application of the classical formula developed by Robert V. Whitman and Frank E. Richart[24]:

$$s_{f,\,s} = Q \times (B/L)^{0,5} \times (1 - v^2) \times (E_0 \times \omega_z)^{-1} \tag{4}$$

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[23] Ibidem.
[24] Ibidem.

where:

B – shorter side of the rectangular foundation (i.e., sleeper width) [m],

L – longer side of the rectangular foundation (i.e., sleeper length) [m],

n – Poisson's ratio,

E – deformation modulus [MPa],

ω_z – coefficient defined by R.V. Whitman and F.E. Richart[25],

Q – vertical concentrated loading force. The authors propose to examine the sleeper section of the length of l_ξ, being a zone covering the rail location and sleeper sections in its direct vicinity. In this zone, referred to as the sub-rail zone, force *Q* is concentrated in the vertical axis of symmetry. The force value equals a half of the vertical thrust of the vehicle's design axle load, i.e., $Q = 0.5 \times 221$ kN.

The correlation between load and settlement of rigid circular plates is based on Lambe and Whitman's formula[26]. It is proposed that settlements of a uniform elastic layer under a uniformly loaded surface (the foundation, i.e., a sleeper, as defined in this article) should be calculated.

One may also apply a specific dependence in order to calculate the settlement of a uniform elastic layer of soil subgrade under the foundation centre of circular surface (in which case, it is difficult to find an appropriate analogy to a railway track structure, however, the foundation in question, i.e., an object imposing a load on the subgrade, may be a VSS plate, typically of the diameter of $d = 0.30$ m, usually used in on-site determination of the track substructure's modulus of deformation on the railway subgrade level)[27].

Assuming that a deformable circular foundation generate uniformly distributed load on the ground medium, the dependence assumes the following form:

$$s = q \times d \times w_1 \times w_2 \times w_3 \times (1 - \nu^2) \times E_g^{-1} \quad (5)$$

where:

q – mean value of vertical stresses under the foundation, at the contact with the subgrade [MPa],

d – foundation diameter [m],

E_g – Young's modulus of elasticity of the ground medium in the zone located directly underneath the foundation footing [MPa],

w_1 – impact coefficient whose value depends on various factors including modulus E_g, foundation diameter *d* and linear increment of modulus E_g along with the depth in the ground medium (the value of coefficient w_1 [-] is to be determined

[25] Ibidem.
[26] Ibidem.
[27] Ibidem.

by reading the nomogram provided in the publication Regulation of the Minister of Transport [28]),

w_2 – correction factor entailing the foundation rigidity [-],

w_3 – correction factor entailing the foundation footing depression [-],

v – Poisson's ratio [-].

Important formulae were developed by George G. Meyerhof for rectangular foundations[29]. Foundations of such a shape may constitute an analogy to a railway sleeper. Settlement or a foundation loaded in a uniformly distributed band of the value of q [MPa], set upon a homogeneous and elastic layer (with reference to a railway track, an appropriate equivalent of such a layer would be a broken stone ballast, typically of granite or basalt breakstone) spread across a non-deformable subgrade, can be calculated according to the following formula:

$$s = q \times B \times w_s \times E_g \tag{6}$$

where:

B – foundation (sleeper) width [m],

w_s – settlement impact factor [-],

E_g – Young's modulus of elasticity of the ground medium forming the subgrade [MPa].

The settlement value according to formula (6) is obtained at the corner of a rectangular foundation. However, settlement values at the rectangle centre are calculated based on superposition of the calculation results for four rectangles jointly forming the foundation surface. The w_s settlement impact factor, i.e., the influence of the non-deformable subgrade layer, is determined based on nomograms, depending on the type of soil forming this layer, and the h/B quotient (where h is the subgrade depth covering what is referred to as the active zone, and B is the foundation width). A distinction has been made between cohesive ($v = 0.5$) and non-cohesive ($v = 0.3$) soils. The parameter applied in nomograms with regard to the soil type is coefficient λ_p correlated with Poisson's ratio v by means of the following dependence:

$$\lambda_p = v \times (1 - 2v) \times (1 + v)^{-1} \tag{7}$$

[28] Rozporządzenie Ministra Transportu, Budownictwa i Gospodarki Morskiej z dnia 25 kwietnia 2012 r. w sprawie ustalania geotechnicznych warunków posadawiania obiektów budowlanych, Dz.U. poz. 463.

[29] M. Drusa, M. Moravčik, op. cit.; M. Drusa, "Vhodnost' pouzitia klasickych...", op. cit.; M. Drusa, J. Benda, op. cit.; M. Drusa, B. Prelovsky, op. cit.; A. Surowiecki, op. cit.

An assumption particularly important for a railway track is the aforementioned **non-deformability**. At this point, a reference should be made to technical railway guidelines currently applicable to a track substructure [Id3-D4], which require that modulus of deformation of the value at least equalling $E_{p,\,t}$ = 120 MPa should be ensured for the plane of a subgrade for a main railway line superstructure. If, for the sake of compliance with the mentioned requirement, the railway line designer is obliged to perceive the subgrade as non-deformable 'to a certain extent', then it seems permissible to apply formula (6) in the sphere of railway engineering.

Another formula applicable to a rectangular foundation is a solution proposed by James D. Brown[30], namely to estimate settlements under a continuous footing loaded with concentrated force. As an analogy to this case, one may refer to a railway sleeper section (rectangular) loaded with a vertical concentrated force of 0.5 × Q (where Q is the train axle load) applied at the point of the rail attachment to the sleeper. Settlement of values for the footing are read from J.D. Brown's nomogram depending on the $k_{f,\,g}$ rigidity coefficient [-] determining strength characteristics of both the foundation and the subgrade. The value of coefficient $k_{f,\,g}$ is established based on the following equation:

$$k_{f,\,g} = 16\, E_f \times I_f \times (1 - v^2) \times (\pi \times E_g \times L^4)^{-1} \tag{8}$$

where:

$E_f \times I_f$ – flexural rigidity of the continuous footing (E_f – deformation modulus of the continuous footing material [MPa], I_f – moment of inertia of the continuous footing cross-section against the central principal axis perpendicular to the plane of loading [m^4]),

v – dimensionless Poisson's ratio characteristic of the foundation material,

E_g – modulus of deformation of the ground medium in the foundation subgrade [MPa].

There is a well-known method of calculating settlements s [m] of a rectangular foundation slab (L – length [m], B – width [m]), uniformly loaded across the entire surface. The slab is founded on a uniform, elastic isotropic layer (its analogue may be a broken stone ballast used in railway engineering) of the thickness of h [m]. The settlement calculation formula is as follows:

$$s = q \times B \times (1 - v_g^{\,2}) \times w_{w,\,f} \times w_{w,\,g} \times E_g^{-1} \tag{9}$$

[30] M. Drusa, M. Moravčik, op. cit.; M. Drusa, "Oporne konstrukcie dopravnych stavieb", op. cit.; M. Drusa, "Vhodnost' pouzitia klasickych...", op. cit.; M. Drusa, J. Benda, op. cit.; M. Drusa, B. Prelovsky, op. cit.; A. Surowiecki, op. cit.

where:

$w_{w,f}$ – impact factor read from the relevant nomogram, depending on the k_u rigidity coefficient [-] and the L/B ratio, assuming that $h/B = \infty$ (under the assumption, there is only an elastic layer of the thickness of h),

$w_{w,g,n}$ – factor of the non-deformable layer's impact below the level of the foundation setting, determined based on the nomogram for the envisaged values of k_u [-] and the quotient of h/B [-] (a case of a non-deformable layer occurring under a set composed of the foundation and the elastic layer).

Other symbols have been assumed following previous formulae.

The k_u rigidity coefficient applies to the entire structure consisting of two components: the foundation and the soil subgrade. This coefficient may be referred to as a generalised one, since it combines essential characteristics of the mentioned components (moduli of deformation and Poisson's ratios)[31]: E_f, v_f – foundation parameters; E_g, v_g – subgrade characteristics.

When the above model is referred to a railway track structure, the set of components is to be understood as follows (starting from the top): sleeper loaded by the vehicle axle load + broken stone ballast (broken hard rock aggregate, e.g., granite, syenite, basalt) treated as the elastic layer + non-deformable subgrade layer. The subgrade assumed for a main railway line superstructure may be approximately treated as non-deformable, provided that one has ensured a minimum value of the modulus of deformation on the subgrade level, i.e., $E_{0,\,min} = 120$ MPa, according to the relevant technical conditions[32].

Eurocode 7 recommends that settlement differences resulting from the subgrade inhomogeneity should be calculated, with the reservation that legitimacy of the calculations should depend on the structure rigidity. Bearing in mind what is referred to as a railway track grate, founded on a layer of broken stone ballast, and despite the tendencies to build rigid superstructures, particularly in main railway lines (using heavy rails, attaching rails to sleepers which precludes even minimum rotations of rails against the sleepers in the vertical plane, by appropriate anchoring of the track grate in the ballast layer ensuring the required resistance to transverse and longitudinal track displacement), one can expect local deterioration of the structure rigidity. Such situations may be encountered in zones of classical rail contacts, near railway stations or on routes of instable track substructure.

[31] Rozporządzenie Ministra Transportu, Budownictwa i Gospodarki Morskiej z dnia 25 kwietnia 2012 r. w sprawie ustalania geotechnicznych warunków posadawiania obiektów budowlanych, Dz.U. poz. 463; A. Surowiecki, op. cit.

[32] Ibidem.

The value of settlement difference measure Δs^* can be calculated based on the following formula[33]:

$$\Delta s^* = \Delta s \times (l_0)^{-1} \quad (10)$$

where:

Δs – difference in settlements of two adjacent foundations analysed (sleepers, in the case of a railway track),

l_0 – distance between centres of footings in the foundations analysed (in a railway track, l_0 is contained in the range of 0.6-0.65 m).

It is believed that those measures can be applied to other structures as well. In this respect, the category of 'other structures' may also include a track grate which consists of sleepers (foundations) uniformly spaced and linked with rails, founded on the subgrade with a ballast layer (forming a two-layer track structure: superstructure + ballast + soil subgrade) or with ballast and a protective layer. According to the latest solutions applied in structures of main railway lines, in order to obtain a modulus of deformation of $E_0 \geq 120$ MPa at the subgrade level, a multi-layer system of the track substructure is recommended[34]. Therefore, the strengthening layer may be a conglomerate, for instance, forming a complex system comprising the following elements (starting from the subgrade level): geotextile separating mat + geosynthetic mesh taking over tensile stresses + mechanically stabilised stone aggregate layer.

In the discourse on the measures of settlement and settlement differences, one should consider the contents of the national annex for Poland to Eurocode 7[35]. It is recommended that values of the following measures should be verified:

1) $s_{z,\,max}$ – vertical structure displacement being a measure of maximum foundation settlement [m],

2) $\theta_{max,\,1-2} = \Delta s_{max} \times (l_0)^{-1}$ – structure deformation parameter, where:

Δs_{max} – maximum difference between settlements of two adjacent foundations [m],

l_0 – distance between centres of footings of foundations No. 1 and 2 being analysed [m],

3) $\theta_{max,\,1-3}$ – structure deformation parameter, determined based on settlements of three foundations for which the value obtained for this measure is the largest.

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[33] A. Surowiecki, op. cit.

[34] Rozporządzenie Ministra Transportu, Budownictwa i Gospodarki Morskiej z dnia 25 kwietnia 2012 r. w sprawie ustalania geotechnicznych warunków posadawiania obiektów budowlanych, Dz.U. poz. 463; A. Surowiecki, op. cit.

[35] PN-EN 1997-1: 2008, op. cit.; PN-EN 1997-2: 2007, op. cit.

A natural phenomenon considered an issue in geotechnics is the subgrade stratification. For such cases, it is proposed that the modulus of elasticity E_{elast} in formula (2) should be substituted with an averaged modulus (weighted mean value) as proposed by Joseph E. Bowles[36]:

$$E_{elast,\,mean} = (H_1 \times E_1 + H_2 \times E_2 + \ldots + H_n \times E_n) \times H_c^{-1} \tag{11}$$

where:

H_i – thickness of individual subgrade layers [m],
E_i – values of moduli of deformation for individual subgrade layers [MPa],
H_c – thickness of the active subgrade layer [m].

As regards the summation method for denominations of the subgrade layers, Eurocode 7 defines a sequence according to which the total foundation settlement is calculated regardless of the subgrade soil type:

1) calculation of the distribution of subgrade stresses caused by the foundation service load (i.e., the railway track sleeper in the understanding of the monograph's field of study); it is permissible that one should apply the theory of elasticity and a linear distribution of stresses under the foundation when assuming a homogeneous and isotropic ground medium,

2) calculation of deformation occurring in the subgrade, caused by the service load; one applies the relevant values of moduli of deformation E_0 or of dependence $\sigma = f(\in)$, determined based on laboratory or field tests,

3) summation of vertical deformations, thus obtaining the total settlement; one must bear in mind that a sufficient number of points in the subgrade should be assumed below the foundation (sleeper) level.

Where Eurocode 7 approves the procedure of settlement calculation in accordance with standard PN-81/B – 03020[37], then following the provisions of this standard, one may calculate the values of stresses occurring in individual subgrade layers by application of the corner point method.

Concluding the discussion on the settlement estimation for direct foundations according to the provisions of Eurocode 7, the following issues should be emphasised:

1) having established characteristics of the soil subgrade (i.e., substructure, to be more specific, when referring to a railroad) and structure category (e.g., main railway line – category 0[38] which determines the permissible settlement values and settlement differences, one should:

– develop a detailed subgrade testing specification,

[36] A. Surowiecki, op. cit.
[37] PN-81/B-03020, op. cit.; PN-EN 1997-1: 2008, op. cit.; PN-EN 1997-2: 2007, op. cit.
[38] W. Kozłowski, A. Surowiecki, op. cit.; A. Surowiecki, op. cit.

– assume appropriate models proposed by mechanics of geomaterials and choose an appropriate calculation method,

2) by following simplified theories applied to establish the settlements (e.g. simplified elastic medium method based on solutions derived from the theory of elasticity, generally discussed in annex F to Eurocode 7), one should not expect fully reliable results, but merely estimated settlement values.

4. Concluding remarks

In this article, an overview of problems related to railway track design in Poland has been given against the background of European regulations (Eurocode 7) as well as related Polish guidelines. The standards are a useful way of using know-how and create similar conditions that have to be fulfilled in each country, which creates opportunities for exchange of knowledge and experience between different countries. However, as the discussion in this paper shows, the Eurocode 7 is rather complex, and not perfect. As Krystyna Wiśniewska[39] argues, while Eurocode 7 constitutes a valuable selection of technical know-how, the mentioned complexity makes applicability in all cases questionable. Standards can be used in case of predictable situations, and lower costs of developing large infrastructural projects. This may be relevant for local roads and railroad tracks in, for example, peripheral areas. However, railroad construction is most of the time a large-scale project, where standards are needed to deal with the complex nature of the venture. Even when the Eurocode 7 is complex, it reduces the complexity of large projects, and creates possibilities to learn from projects in other countries.

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Projektowanie torowiska kolejowego w odniesieniu do wymogów standard Eurokod 7

Streszczenie. Autorzy artykułu omówili Eurokod 7 jako zestaw wymogów i ogólnych rekomendacji dla projektowania geotechnicznego z punktu widzenia podtorza kolejowego oraz eksploatacji układu torowego. Poruszana problematyka obejmuje podstawy projektowania struktur geoinżynieryjnych, warunki wyszczególnione w Eurokodzie 7 w celu zwiększenia nośności i obciążenia podtorza, a także rekomendacje ujęte w Eurokodzie 7 odnoszące się do bezpośrednich założeń dotyczących kolejowych układów torowych. Specjalny nacisk położono na modele służące do obliczania bezpośrednich założeń oraz możliwości zastosowania ich podczas projektowania torowiska. W podsumowaniu omówiono wybrane opinie oraz komentarze dotyczące Eurokodu 7, zawarte w publikacjach geotechnicznych.

Słowa kluczowe: tor kolejowy, projektowanie podtorza, Eurokod 7