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Reliability of the geotechnical data for the modernization and repair of railways

Abstract: The article concerns the rules and guidelines used for geotechnical design, subsoil investigation procedures and geotechnical investigation methods of railway lines. The discussion of the soil investigation methods, which provide reliable geotechnical data for the modernization and repair of railway lines, is presented. The article describes a comprehensive example of errors made during the programming and performing of soil investigations in the modernized railway line. The impact of soil investigation errors on the slope stability of the railway embankment is discussed.

Keywords: Railway embankments; Subsoil; Geotechnical investigation

Introduction

Intensive activities in design and construction concerning the modernization of railway lines have been carried out in our country since the second half of the 90s of the last century. During this period, there were also changes in the rules on testing ground and geotechnical design of the railway.

The article presents regulations in the field of geotechnical design, programming and execution of research on substructure in railways. The discussion was devoted to testing methods that ensure to obtain reliable geotechnical data for the design, modernization and repair of railway lines. We also presented a comprehensive example of the impact of errors in planning geotechnical tests and interpreting the results on design solutions of the section of the modernized railway line.

Guidelines for research of ground for the construction and modernization of railway infrastructure

Basic guidelines for the technical conditions to be met by railway buildings and their location are contained in MTiGM Regulation No. 987 of 1998.[7]. Its records about geotechnical surveys and analysis of the stability of slopes are modest and vague. More specific guidelines were included in the industry standard of 1988. "Substructure of the track and track bed. Earthworks. Requirements and test methods" [3]. However, the passage of time, technological advances and publications about further legislation, significantly outdated regulations of this standard.

Another instruction concerning the maintenance of the railway subgrade issued by the Board of PKP Polish Railway Lines S.A brought following guidelines on ground diagnosis and geotechnical design of railway subgrade. In the instructions for the maintenance of the rail track bed D4 1996. [4] and "Terms of the technical maintenance of the rail track bed" Id-3 (D-4), 2004 [8], geotechnical subjects were considered marginally and records about analysis of embankment stability were absent. These shortcomings have been partially completed in the next edition of the provisions from 2009 in instruction "Technical conditions for the maintenance of the rail track bed Id-3" [9], which provides guidance for the geotechnical design of embankments and geotechnical research of base and substructure, including recommendations on the selection of test points and the range of field and laboratory research. The instruction contains guidelines for various cases of complex and complicated ground conditions in the substrate.

Within a few years after the release of instruction Id-3 of 2009, regulations in the field of geotechnical design and geotechnical testing ground have been significant changed. On 31.03.2010 Polish Committee for Standardization withdrew 39 Polish Standards used for decades in designing practice and replaced them with relevant Eurocodes. In the field of geotechnical design it was introduced Eurocode 7 and a series of standards DIN EN ISO. In this situation, at the request of the Board of PKP PLK SA, it was developed in 2015 the detailed instruction Igo-1 [10] (with the additions in 2016. [11]) for geotechnical testing ground for the construction and modernization of the railway infrastructure, which is fully based on the current standards and regulations. The instruction clearly defines the principles of design work, geological research and project works and geotechnical studies designed to determine the suitability of ground and evaluation of foundation conditions of linear objects. In terms of geotechnical design it is clearly recommended to use Eurocode 7, which is not preferable in all aspects of the design. Authors wrote in the pages of the Review Communication in 2012, about the dangers involved in modernizing railway embankments based on Eurocode 7 and DIN EN ISO [1]. Other fundamental change, considered by the authors as favourable, is the limitation in the use of PN 81/B 03020 [6] for determining values of geotechnical parameters for analysis of stability of slopes of railway embankments.

The instruction Igo-1 [11] is still updating and detailing the current instruction Id-3 in 2009. [9], which carries a very broad range of concepts, definitions and guidelines from Eurocode 7 and its related standards. Their introduction to the design practices in the railway will be a significant challenge for the beaten habits and previously used procedures for programming geotechnical testing and performance of testing ground surface.

An example of improper programming geotechnical studies

To illustrate the mentioned problem we presented an example of the documentation developed in 2015 for the modernization of a two-km stretch of a secondary railway line in the southern Poland, where a routine approach for the selection of the scope and type of geotechnical studies caused necessity their replenishment several times. Obtained results were initially advantageous but verifications carried out by a team of geotechnical revealed a significant threat to the exploitation of the test section of the railway line.

1. stage geotechnical studies

The first data on the geotechnical conditions of the substrate and the embankment were provided by a standard geotechnical documentation comprising 54 boreholes (located on the crown and the base of the slope on both its sides), and 18 dynamic probes carried out in the crown of embankment. The diagnosis was carried out to a depth of 3.0 m below ground level under the embankment and on both sides. Laboratory studies included only a few sieve analysis and determinations of states of cohesive soils. On this basis, for the 18 transverse sections, it was defined system and lithological succession of layers of ground, separated a number of geotechnical layers in terms of the type and condition of the ground as well as the calculated values of geotechnical parameters.

The upper parts of the embankment has been identified as composed of anthropogenic material in the form of a mixture of stones, soil, slag and native soil of variable thickness, generally concentrated in the average state. Below the embankment is formed by cohesive ground with variable coherence (from clayey sands, through silty clay to concise clay), mainly in the hard-plastic state close to plastic with $I_L = 0.20 - 0.24$. In turn, in the slope surface to a depth of 3.0 m was only recognized the occurrence of cohesive soils (especially average cohesive) in a state from hard-plastic to plastic with $I_L = 0.20 - 0.39$.

The established states of cohesive and non-cohesive soil predicted no problems with the corresponding embankment stability and load capacity of the ground. However, in the analysis of this documentation, the claims were raised strikingly by a little variation of the ground layers around the 3-kilometer stretch of the route, in particular, the fact that only one or occasionally two layers of cohesive soils have been separated in each of the generated cross sections in the base of the embankment.

2. stage geotechnical studies

In order to resolve doubts about the accuracy and quality of recognition of geotechnical conditions, additional diagnosis was conducted using static sounding probe CPTU made in research points located on the crown of the embankment in the vicinity to the earlier research of holes for each of the 18 geotechnical sections. The depth of CPTU diagnosis was adopted no less than the depth of previous research drilling.

The results showed the number of discrepancies in the diagnosis of ground, including:

- cohesive ground in the embankment are generally in the plastic state with $I_L = 0.30 – 0.45$ in comparison to hard-plastic state with $I_L = 0.20\text{-}0.24$ found in the previous documentation,
- in the ground, directly below the embankment instead hard-plastic ground cohesive soils in a plastic state were found with $I_L = 0.30 – 0.45$ also in a less favourable condition than previously;
- in the ground for more than half of the tested section, CPTU probing recognized the presence of layers of non-cohesive soil (fine, medium and coarse sand) with varying state of density with $I_D = 0.30 – 0.80$, which were not identified in the previous documentation.

In this situation, these tests cannot be considered conclusive. Given the research methodology of substrate it should be noted that in the case of well-performed drilling test, type and condition of ground is recognized in sample material extracted from the test hole, and in the case of CPTU probing, the type and condition of ground is determined indirectly on the basis of interpretation of the parameters measured in the cone of the probe (resistance q_c and f_s and pore pressure u_2). The assessment of geotechnical conditions based on CPTU research is therefore additionally charged with potential inaccuracies of interpreted formulas, which in particular may be important in the case of anthropogenic (bulk) ground, because the commonly used (e.g. nomograms by Robertson and Młynarka) relate essentially to the native ground.

In the view of the significant differences between the two documentations and to provide additional data, the authors pointed out three sections, in which additional drilling and probing from the crown of the embankment were made in order to verify the type and condition of the ground, as well as it was commissioned to carry out laboratory tests of strength and deformation parameters for representative samples of soil with intact structure and the retained moisture (samples cat. A).

3. stage geotechnical studies

In three of the eighteen representative geotechnical sections additional drilling research and dynamic DPSH probing to a depth of 8.0 m below the crown of the embankment were performed in order to obtain conclusive data for the verification of the described above discrepancies between the two previously made geotechnical documentations.

Comparison of the results obtained in three successive stages of research for three geotechnical sections are contained in Tables 1 - 3. There are significant differences in separating vertical limits of different types of ground as well as differences in their states.

The obtained results were in full agreement with evaluation of cohesive state of soils of slope defined CPTU research (stage 2), and in verifications (stage 3). For cohesive ground of embankment partial compliance of results was achieved. The verification tests indicated the presence of grounds in a more unfavourable conditions, in plastic and soft-plastic states with I_L=0.35-0.51 than those defined using static probing.

It cannot be ruled out that the differences between the vertical separation of the layers due to the high variability of the layers of the substrate of railway embankment.

Table 1. Comparison of the results of physical parameters of grounds in section 8

Type of layer	Stage 1 drilling research		Stage 2 static probing		Stage 3 Verification studies	
	passage	state	passage	state	passage	state
Embankment – cohesive ground	1.6 – 3.6 m	I_L = 0.21	1.2 – 2.0 m 2.0 – 3.8 m	I_L = 0.25 I_L = 0.45	1.4 – 2.8 m	I_L = 0.47
Substructure - cohesive ground	3.6 – 6.5 m	I_L = 0.21	3.8 – 4.5 m	I_L = 0.45	2.8– 3.6 m 3.6-4.8 m	I_L = 0.47 I_L = 0.35
Substructure – non-cohesive ground	NA	-	4.5 – 6.2 m 6.2 – 7.5 m	I_D = 0.48 I_D = 0.80	4.8 – 6.4 m 6.4 – 8.0 m	I_D = 0.66 I_D = 0.83

Table 2. Comparison of the results of physical parameters of grounds in section 12

Type of layer	Stage 1 drilling research		Stage 2 static probing		Stage 3 Verification studies	
	passage	state	passage		passage	state
Embankment – cohesive ground	1.5 – 4.3 m	I_L = 0.21	0.2 – 3.4 m	I_L = 0.40	0.6 – 3.2 m	I_L = 0.40
Substructure - cohesive ground	4.3 – 7.5 m	I_L = 0.33	3.4 – 5.4 m	I_L = 0.40	3.2 – 4.7 m 4.7 – 7.3 m	I_L = 0.14 I_L = 0.51
Substructure – non-cohesive ground	NA	-	5.4 – 6.1 m 6.1 – 7.5 m	I_D = 0.30 I_D = 0.60	7.3 – 8.0 m	I_D = 0.73

Table 3. Comparison of the results of physical parameters of grounds in section 15

Type of layer	Stage 1 drilling research		Stage 2 static probing		Stage 3 Verification studies	
	passage	state	passage		passage	state
Embankment – cohesive ground	1.9 – 3.2 m	I_L = 0.22	0.6 – 3.2 m	I_L = 0.30	1.4 – 3.2 m	I_L = 0.41
Substructure - cohesive ground	3.2 – 6.0 m	I_L = 0.22	3.2 – 5.8 m	I_L = 0.35	3.2 – 4.4 m 4.4 – 6.4 m	I_L = 0.20 I_L = 0.41
Substructure – non-cohesive ground	NA	-	5.8 – 6.8 m 6.8 – 8.0 m	I_D = 0.50 I_D = 0.30	6.4 – 8.0 m	I_D = 0.64

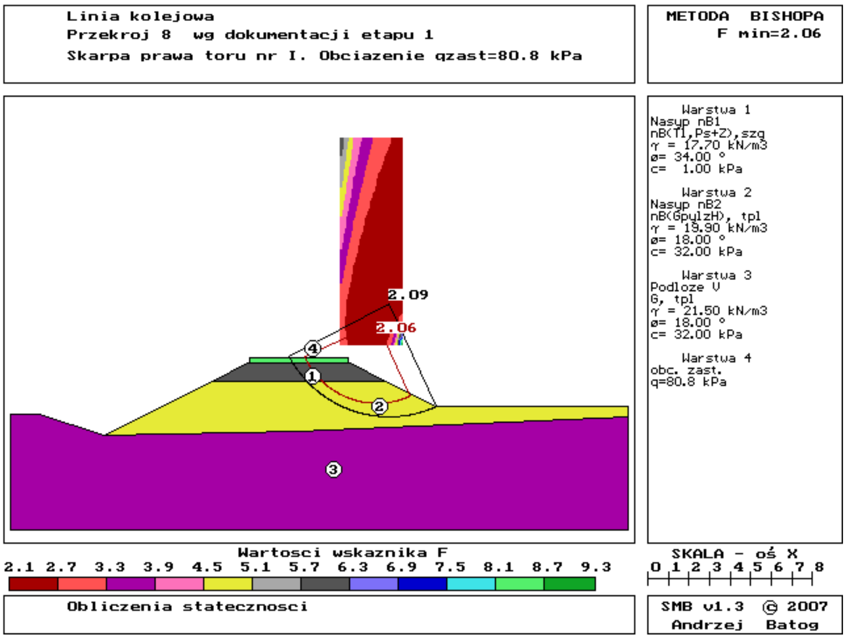
The influence of different assessments of physical state of ground on the embankment stability

The geotechnical documentation of the first phase of research for cohesive soils forming embankment indicated a significantly lower (better) values of plasticity than those specified in the remaining two publications (phase 2 and 3 of studies). This has a significant impact on the assessment of the stability of soil embankment slopes loaded with the weight of the rolling stock moving with the scheduled speed. This is illustrated in Figure 1, which shows the results of calculations of stability in section 8, made by Bishop's method for the ground conditions and geotechnical parameters specified in the first phase of research. The tolerance of stability is here high, the stability rate (coefficient of confidence) $F_{min} = 2.06$ in comparison to the value required by the instruction Id-3.

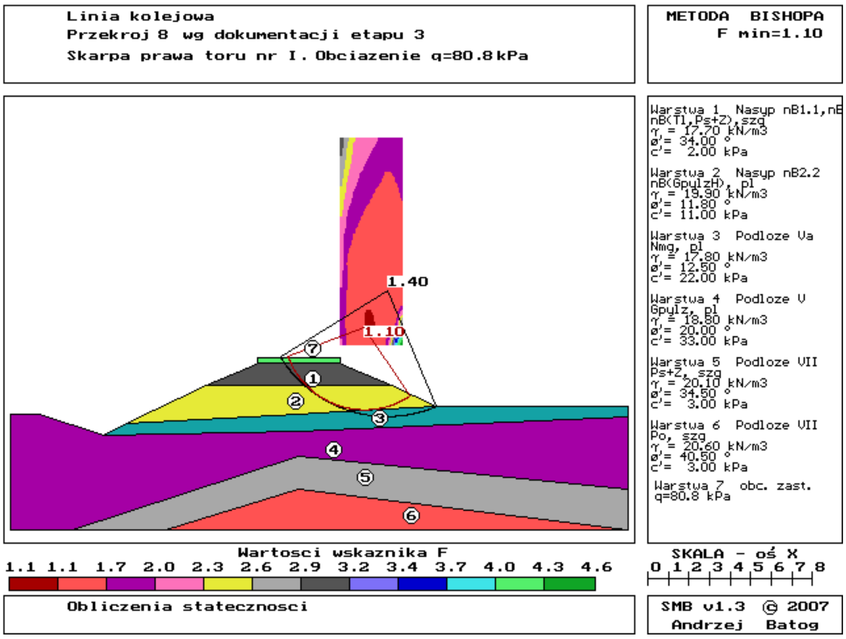
Much more unfavourable assessment of the stability are provided by researches from the phase 2 and 3, as they recognized cohesive grounds in a plastic state in the embankment $I_L=0.40\text{-}0.47$ can be characterized by insufficient resistance to shear, not providing achievement of the required tolerance for the stability of the embankment slopes. A smaller, but also disadvantageous influence on the stability of the embankment slopes is the occurrence of cohesive soils in the plastic and soft-plastic state with $I_L=0.35\text{-}0.51$ in the deeper parts of the substrate. Analogous calculations of stability were made in section 8 of the ground conditions identified in the 3rd phase of the study brought the stability ratio (ratio of certainty) of only $F_{min} = 1.10$. It is the state close to the balance limit.

This way of determining the value of geotechnical parameters, including in particular parameters of resistance to shear has a significant impact on the results of assessments of the stability of embankments [5]. In the documentation of phase 1 of research, physico-mechanical parameters of separate layers of grounds have been determined only by means of correlation dependence, without carrying out any specific research. The actual values of geotechnical parameters may vary significantly from these values. In order to perform reliable stability calculations, the authors pointed sites for sampling soil with undisturbed structure to determine in laboratory methods reliable characteristic values of geotechnical parameters: volume density ρ and proper density ρ_s, consistency borders w_p and w_L, effective value of cohesion c' and the angle of internal friction φ'.

As a result of the conducted subsequent stages of the geotechnical studies it was achieved that a reliable assessment of the stability level of the existing section of the modernized railway route which was the basis for the adoption of rational design solutions.



1. Cross section 8. Calculation of stability for the diagnosis of ground conditions from stage 1 study - a very high tolerance of slope stability of the embankment



2. Cross section 8. Calculation of stability for the diagnosis of ground conditions from stage 3 study - a very low tolerance of slope stability of the embankment

Summary

The presented in the article example of stability analysis fo modernized fairly short section of railway track clearly shows the significant influence of the quality of diagnosis of soil-water conditions of the existing substructure.

The current experience the authors associated with the problems of designing new or upgrading earthen railway structures proves the necessity of responsible programming geotechnical studies and professional interpretation of their results.

Multistage realization of recognition of geotechnical substructure recommended in the recent "Guidelines..." [10], [11] is correct, but rarely implemented, usually in an emergency of failure of railway infrastructure that is modernized or repaired. Hence, most often, the first stage of the geotechnical studies is only and becomes a significant fundamental research.

Whether geotechnical recognition substructure will be carried out in one or several stages, their programming should be preceded by careful terrain vision of the modernized section or designed rail route with inventory of situation which may affect the quality of life of the line.

Another very important and economically reasonable action in programming research is the collection and analysis of all available geotechnical information for the area with the use of archival documentation, geological databases, etc. Modern programming geotechnical studies, according to the Eurocode 7 prefers field testing with the restricted role of laboratory studies taken from test holes of soil samples to determine the classification parameters and perform selected studies of mechanical features.

Programming research, not only for the construction and modernization of the railway infrastructure, it should be taken into account the goal of this research, which is often forgotten. The aim is to obtain reliable data for specific numerical analyses of the overall stability of the given object and its behaviour under the expected outer impacts.

As a result, the solution of tasks in the form of obtaining reliable geotechnical data, in particular for linear objects of railway infrastructure, should not be based solely on the results of studies carried out one of the trendy or available techniques such as static CPTU probing or only small diametric drilling in points significantly distant from each other. In this case, the point diagnosis should be completed with geophysical surveys or GPR profiling which has been tested as part of the modernization of several railway lines in the south and east of the Poland. Such requirement also applies to the design of road embankments.

Field tests if they are programmed in the form of drilling and static or dynamic probing should complement each other because the interpretation of the static probing can lead to incredible assessments of geotechnical data.

The scope of laboratory testing of soil samples, and in particular anthropogenic materials, is designed to assess the reliability of the geotechnical parameters, which will be suitable for the adopted computational models. This applies to identification of effective shear strength parameters, and parameters for the assessment of deformations of ground buildings under loading.

The above-mentioned observations arising from the previous professional experience of the authors of this article, characterize the process of obtaining reliable geotechnical data for the construction and modernization of railway line constructions as very responsible activity and often requiring the cooperation of geotechnicans with designers.

Source materials

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