MATEC Web of Conferences **262**, 11002 (2019) https://doi.org/10.1051/matecconf/201926211002
KRYNICA 2018

Geotechnical design of railway embankments – requirements and challenges

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Abstract. Intensive development of railway infrastructure in Poland is associated with significant support provided for that purpose by the European Union, especially, by investments in the modernization of existing railway lines. Together with the improvement of the infrastructure in less developed countries, an interoperability of rail system at the international level is sought through the technical harmonization, mostly by the introduction of European regulations and technical standards. The paper presents the main requirements associated with the geotechnical aspects of design of railway embankments, mostly relating to their overall stability and maintenance of serviceability. Some aspects of the European standards as well as international, national, and internal regulations, are discusses in the context of challenges encountered by designers. The main geotechnical issues are associated with safety requirements, loading conditions, geometry of railway embankments, as well as the scope of geotechnical investigation necessary to make an informed decision on a final design solution.

1 Introduction

As the investments into the modernization and development of railway infrastructure in Poland increase, so does the need to rationally balance the reliability levels with the economy of the design. Especially the problem of upgrading the existing lines, most of which are decades old, is a considerable challenge. With insufficient funding, over the years, most of the maintenance effort has been put into the upkeep and renovation of existing track systems, to prolong the serviceability of the most important lines.

One of the main challenges is the construction of new, as well as the use of existing railway embankments. Especially the latter case often poses some challenges, as the construction of many, now 50-70-years old embankments was conducted often with insufficient quality control, when judged by the current standards, as well as with the use of poorly graded local materials or from adjacent cuttings, and placed as uncompacted fill. Later, during the use of these railway lines, in case of excessive settlement, only compensation by addition of ballast has been performed in order to fulfil serviceability criteria and maintain the operation of the line.

The years of neglect, as well as the lack of real renovations and reconstructions, resulted in accumulation of problems which the industry currently has to face. When subjected to years of operation under dynamic loading and varying environmental conditions, such embankments are often hardly suitable for further use without additional measures, to increase their stability, or their demolition and reconstruction according to current standards. Similar problems are known to exist in other countries [1], as well.

However, with the large funds provided by the European Union for the development of railway infrastructure, significant investments into renovation and upgrade of the lines gives an opportunity to make up for years of insufficient upkeep. Additionally, the European Union Agency for Railways (ERA), following the directive of the European Parliament [2], aims to increase the interoperability of European railway infrastructure. Alignment with European standards is seen as one of the elements ensuring it within the European Union.

Generally, the requirements concerning the expected reliability levels in regard to the safety and serviceability of railway lines are regulated by national regulations [3], standards [4], as well as specifications of the railway operator [5, 6]. The construction or modernization of a railway line requires a risk assessment and consideration of possible issues in a design. In regard to geotechnical engineering, these issues are mostly: the stability of embankments and prediction of settlement of railway tracks. In a limit state design framework, these represent the most important ultimate and serviceability limit states, respectively. Proper design also requires the understanding of differences between drained and undrained conditions, depending on the type of material in the embankment and the subsoil.

The main factors guiding the occurrence of these limit states are: railway traffic load, geometry of an embankment, as well as geotechnical conditions (Fig. 1).

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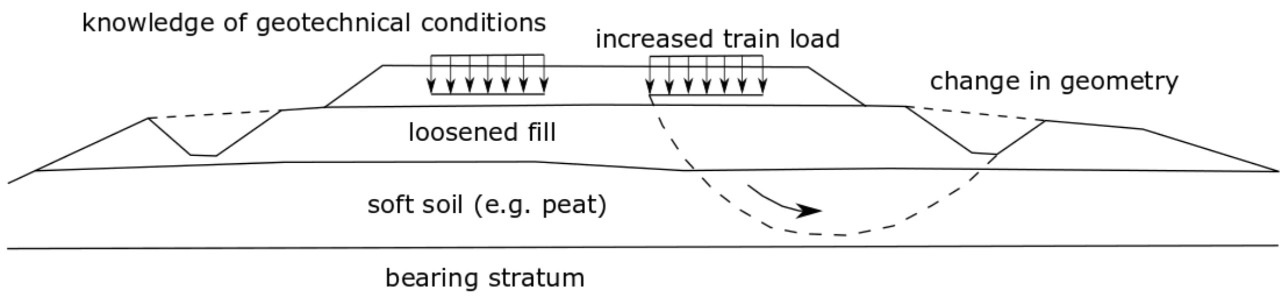

Fig. 1. Main factors guiding the occurrence of limit states for railway embankments.

2 Stability requirements

Usually, the main limit state that has to be considered, in order to ensure safety and sufficient reliability of a railway embankment, is the overall stability under the traffic load. The possibility of a loss of stability is often mostly affected by the imposed loads, the geometry of the embankment, as well as the ground conditions. Therefore, assumptions concerning loading conditions, designed geometry or any implemented changes, and the knowledge of geotechnical conditions, are the main aspects that a designer has to establish before the analysis (Fig. 1). Furthermore, with loading conditions characteristic for railway lines (i.e. cyclic and fast occurring loading), when fine grained soils are present, usually both drained and undrained stability analysis should be considered. The former include the effective stresses analysis σ' (Fig. 2a) with the use of effective strength parameters (φ' – angle of shearing resistance; c' – effective cohesion) for the soil, while the latter is performed for total stresses σ (Fig. 2b) and undrained shear strength c_u should then be used.

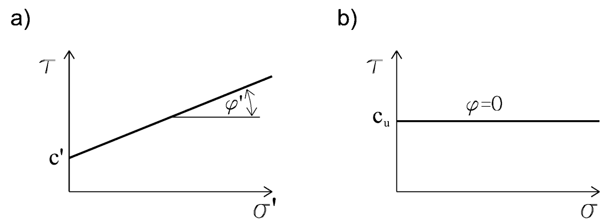

Fig. 2. Shear strength in case of: a) effective stresses analysis, b) total stresses analysis.

Another aspect for consideration, is the reference reliability level, considered to provide sufficient margin of safety. In stability analysis, it can be considered in terms of global safety factor, partial safety factors, reliability index or probability of failure. Generally, it should be established by a railway line operator as a targeted safety level that a designer should achieve.

2.1 Global safety factors

The concept of a global safety factors is based on the assumption that characteristic values of loads, parameters, and resistances are used, and a one lumped factor of safety is applied to ensure that sufficiently low probability of failure is achieved. This approach was often used in the past for many geotechnical problems and do not provide a good representation of safety level, but it is intuitively understood by most engineers and non-engineers.

This approach in stability analysis is still often used for railway embankments. The values of global safety factors, still in use and required by the railway specification Id-3 [6] are as follows for:

- new railways - $F = 2,0$;
- operated railways - $F = 1,5$;
- railways immediately after repair - $F = 1,3$.

Generally, this approach can be associated with qualitative assessment of probability of failure [7] and it is based on previous experience and practice.

2.2 Partial safety factors

Current European standard used for design and consideration of overall stability is the Eurocode 7 [4]. It presents the current state-of-the-art practice within the limit state design framework based on the application of partial safety factors. For the purpose of overall stability assessment according to the National Normative Annex (NNA) to the Eurocode 7 [4], the design approach 3 and the following combination of partial safety factors sets should be used:

$$\text{A2 “+” M2 “+” R3} \tag{1}$$

In this combination, the design parameters are obtained with the use of following partial factors:

- permanent actions: $\gamma_G = 1,0$;
- variable actions (i.e. railway traffic): $\gamma_Q = 1,3$;
- effective angle of shear resistance: $\gamma_{\varphi'} = 1,25$;
- effective cohesion: $\gamma_{c'} = 1,25$;
- undrained shear strength: $\gamma_{cu} = 1,4$;
- resistance: $\gamma_{R;e} = 1,0$.

In contrary to the global safety factor approach, the design verification with the partial factors can include a check of the level of utilization μ, which represent the ratio of design effects of the actions E_d to the design resistance R_d, which are based on abovementioned partial factors:

$$\mu = \frac{E_d}{R_d} \le 1 \quad (2)$$

When the value of this ratio is lower than or equal to one, the design has sufficient margin of safety as required by the code [4]. More information on this subject and the application of partial factors in stability analysis can be found in [8]. Furthermore, this approach had been considered for stability analysis in railway embankments by PKP PLK [9], but it was not implemented as an official specification.

2.3 Reliability based design

The concept of Reliability Based Design (RBD) is gaining more favour among researchers and engineers. It is based on an assumption that the design uncertainties are directly taken into account in calculations and verification is conducted by comparing a predicted probability of failure with the maximum allowed one for a specific structure and mode of failure under consideration.

Even if it is not directly applicable in the everyday design, this concept may offer a way to better balance reliability with cost-effectiveness. For example, in Denmark, Eurocode-based approach to the design of railway embankments has been considered as over-conservative and the probabilistic based approach was proposed [10]. It can be used either directly or as a way of calibrating partial safety factors to be more suitable for the specific application in railway embankment design.

2.4 Design calculations

For design purposes, stability analysis is conducted almost exclusively with the use of numerical methods. These may be based on traditional, analytical solutions, with iterative approach (Fig. 3), or more advanced methods like finite element method (FEM) (Fig. 4).

The former approach better suits as preliminary assessment technique when large number of cross-sections along the railway line have to be analysed. The main advantages of such methods are the low number of input parameters as well as relatively shorter time for model preparation and of calculation. However, they are based on assumed failure surfaces, which may not provide the worst case scenario for more complex geotechnical conditions and may not accommodate introduction of additional structural elements.

FEM should be considered for detailed analysis of selected cross-sections, which preliminary assessment may point out as problematic. Although it requires more data for implementation, its main advantages are that the possible failure surface is not assumed *a priori* but it is a result of the calculations (Fig. 5), as well as it may serve for design of reinforcement or soil improvement. Additionally, with appropriate parameters provided, the same calculations can provide the prediction of deformations at the specific cross section. When it is justified, FEM may be used as well for analysis of spatial problems (3D).

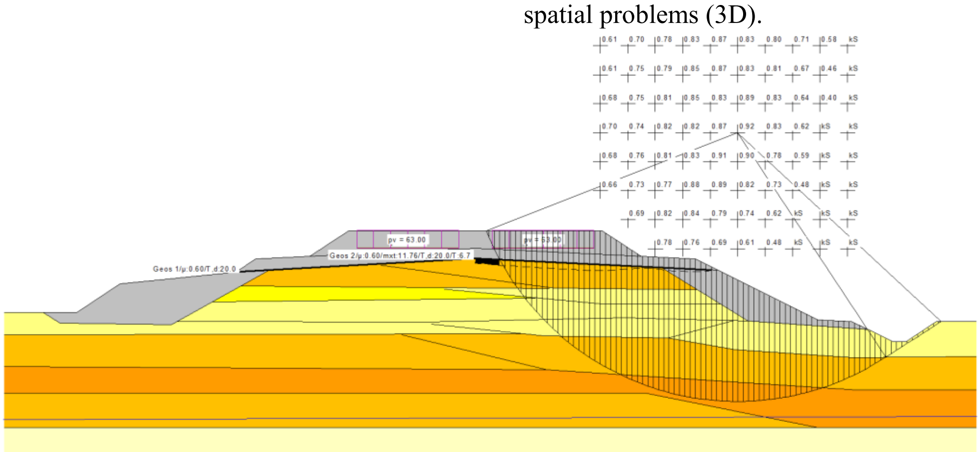

Fig. 3. Example of a model and results of iterative calculations with assumed failures surfaces.

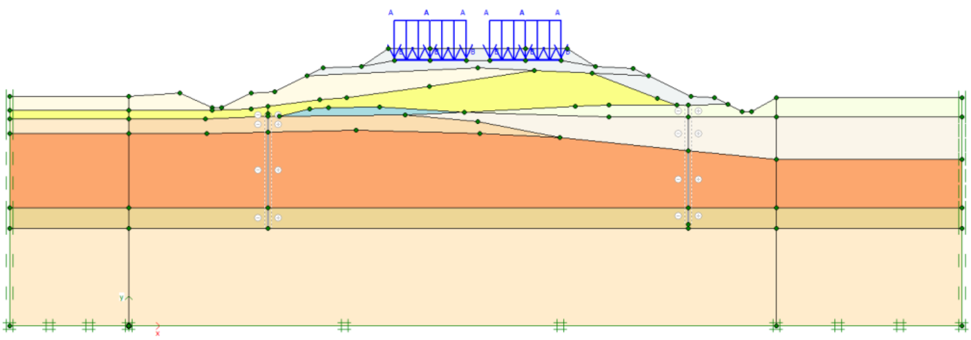

Fig. 4. Example of a FEM model.

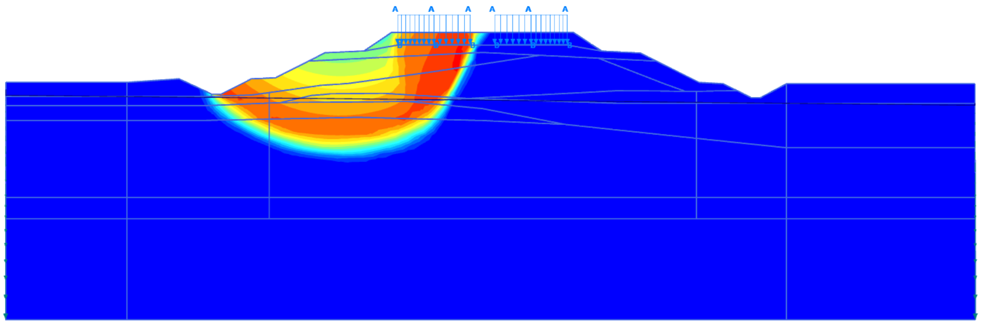

Fig. 5. Example of predicted failure surface with the use of FEM.

3 Serviceability requirements

The second aspect of importance in design of railway embankments is the serviceability of a railway line, which is primarily associated with differential settlement along the line.

If no other values have been specified, PKP PLK [6] requires that settlements of railway tracks should not exceed 4 mm/year over a distance of 30 m and 10 mm/year over 200 m. Moreover, the method from PN-81/B-03020 [11] is recommended for settlement assessment. Should these values be exceeded, soil improvement is required, especially as one of the possible settlement reduction methods for railways over soft and consolidating soils.

Furthermore, to assess the measurement results in regard to different deformation parameters of the railway track, PKP PLK [5] requires more specific parameters to be verified, depending on the type of measurements and the speed of the train allowed at the line.

The detailed analysis of soil-structure interaction in the case of railway lines is generally a complex issue, often significantly simplified for design purposes. A limited research has been conducted so far into this problem, as it is a highly multidisciplinary subject, which includes proper characterization of loads, assessment of dynamic response, load transfer to the subsoil, and finally, the geotechnical conditions and modelling itself.

Generally, response of subsoil, even a relatively soft soil, is mostly undrained and elastic [12]. Furthermore, measurements show that at the depth of 2 m below sleepers, the influence of transient ground movements due to passing train is reduced to negligible values [13]. However, a critical train speed exists above which a track bed failure may occur, resulting in excessive settlement of the tracks [14]. Furthermore, for soft subsoil subjected to self-weight of the embankment, settlement can strongly depend on the long-term consolidation and creep processes.

4 Railway traffic loads requirements

Railway traffic loading has a large influence on the probability of failure for certain failure mechanisms, including overall stability and predicted settlement during the operation of the line. The loads assumed for the design purposes nowadays have to be increased in comparison to previous assumptions as the maximum allowed train speed for the line increases.

Currently, Polish railway authorities [5] accept the methodology presented in the European standard PN-EN 15528 [15], where traffic load is based on the class assigned by PKP. This classification is based on the axle load, line load, geometry of the railway car, as well as the speed.

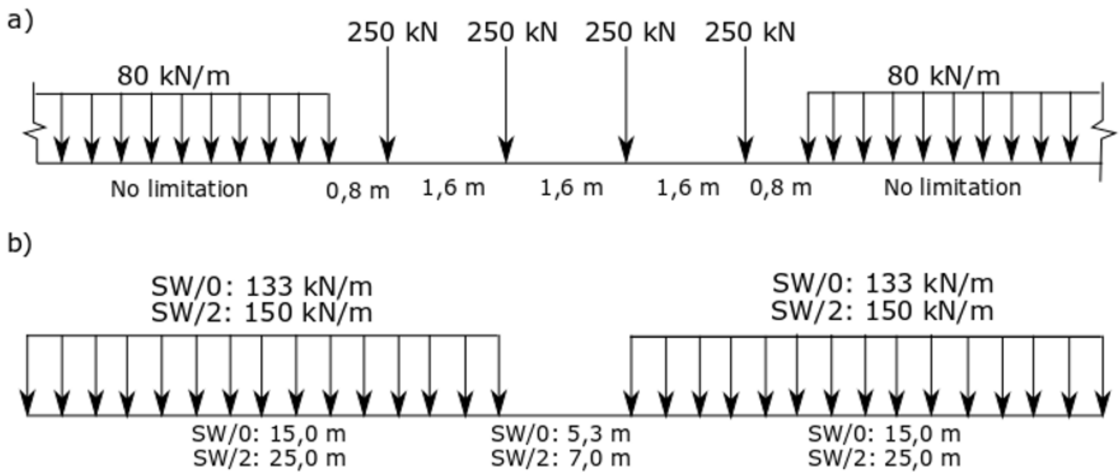

Fig. 6. Load models in PN-EN 1991-2: a) LM 71; b) SW/0 and SW/2.

However, loads in the European standard PN-EN 15528 [15] should be used only for classification purposes of existing structures. For design of new structures, Eurocode 1 and models presented therein have to be used. In coming years, they may be subjected to some changes as the current works on evolution of Eurocodes progress, and the issue of traffic loads has been specifically raised in some of the discussions.

From geotechnical perspective, an additional issue is of importance. Geotechnical calculations for design purposes are conducted primarily for representative cross-sections, perpendicular to the line. This approach requires that the load models specified along the line are transformed into a distributed load, which results in an approximation of given load models for plain strain (2D) representation.

4.1 According to PN-EN 1991

Eurocode 1 [16] distinguishes four different models characterizing rail traffic:

- Load Model 71 (LM71) – Fig. 6a;
- SW (SW/0 and SW/2) – Fig 6b;
- “unloaded train”;
- High Speed Load Model (HSLM).

Normal rail traffic on mainline railways, according to this standard, should be represented by LM71 model, heavy loads by SW/2, and passenger trains at speeds exceeding 200 km/h by HSLM.

Moreover, depending whether the expected load at a specific line is heavier or lighter than normal one, a classified vertical load is derived with the application of a factor α, which can range between 0,75÷1,46.

In regard to geotechnical analysis, according to Eurocode 1 [16], for assessment of global effects, the equivalent characteristic vertical load may be uniformly distributed over a width of 3,0 m at a level 0,7 m below the running surface of the track.

Furthermore, although a dynamically induced response can reach 55% of that generated by the axle load [17], according to the Eurocode [16], no dynamic factor needs to be applied in calculations concerning a geotechnical structure, i.e. an embankment.

4.2 According to PN-EN 15528

The standards [15] is one of the foundations for interoperability of railway infrastructure in the European Union. It includes load models for a range of line categories (A÷E6) as a classification system for existing lines.

In comparison with Eurocode 1 [16], it provides wider range of different load models. Some of them, referenced in specifications of PKP PLK [5], are presented in Fig. 7. The most current version of the standard includes also additional models for very heavy traffic.

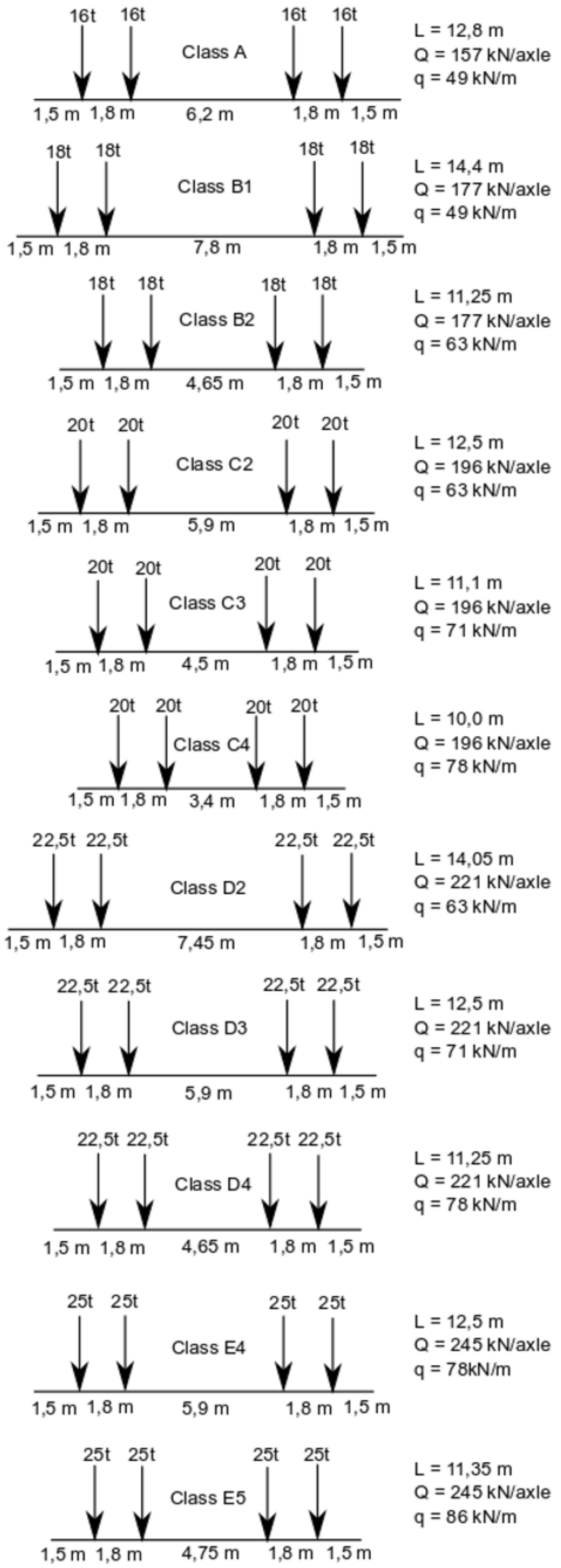

Fig. 7. Load models referenced by PKP PLK [5] from PN-EN 15528 [15].

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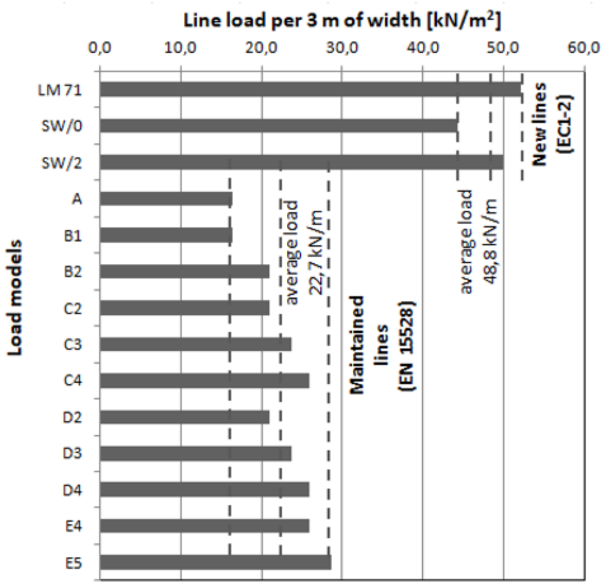

Fig. 8. Approximation of different load models for stability analysis in plain strain conditions.

However, even the heaviest of presented models are characterized by loads lower than resulting from LM71 in Eurocode 1 [16]. Therefore, the requirements for designed structures are significantly higher than for existing ones. For example, when a linear load along the line or approximated one for plain strain conditions is considered in stability analysis (Fig. 8), Eurocode 1 requires the use of 156 kN/m and 52 kN/m^2, respectively. At the same time, the values of these loads resulting from model representing class E5 reach only 86 kN/m and 28,7 kN/m^2, respectively.

5 Geometry

As the existing and designed railway lines are often restricted by available space for a construction of embankments, their geometry is usually guided by factors other than just the stability requirements. Especially, a change of geometry during modernization, often due to drainage construction (Fig. 1), may have a significant impact on stability conditions if soft soil strata are present below the embankment. Cross-section design seldom accounts for ground conditions, as it is not the main area of focus for designers of railway lines.

6 Geotechnical conditions

Often very variable soils, especially for modernized railway embankments, are present along the railway line, which require thorough and risk-based geotechnical investigation.

PKP PLK [68] divides geotechnical investigation into two phases, initial at the planning phase, and detailed at the building permit design phase. However, further investigation should be considered at the executive design phase to further optimize design solutions. Moreover, additional investigation may be required even during the construction. The scope of investigation should aim to decrease uncertainty of the geotechnical design model, sufficiently for a given stage of the project. More specific requirements concerning the scope of investigation were given by PKP PLK [18], based on the joint work of Building Research Institute (ITB), Road and Bridge Research Institute (IBDiM), and Polish Geological Institute (PIG).

When planning geotechnical investigation, the number of test points, when soundings are performed (CPTu, DMT, etc.), should correspond to the number of boreholes. As the boreholes are used for determination of subsoil layering and taking samples for laboratory testing, soundings can provide almost continues profile of a measured parameter. They can then be interpreted to assess geotechnical parameters of the subsoil, with better averaging over the soil mass than based on laboratory tests alone.

Generally, the reliability of obtained ground parameters and assumed geotechnical design model, including cross-sections along the line and perpendicular to it, have a direct impact on reliability of any design calculations. Especially when adopting Eurocode 7's partial safety factor approach, which generally is less conservative than the practice in Polish railway industry so far [3], the scope and quality of investigation should be of utmost concern.

Furthermore, when reliable verification of serviceability in regard to settlements is considered, DMT is highly useful in determination of soil deformation modulus for calculation, as an alternative for more expensive laboratory tests. The correlations applied in practice, between probing results and information on soil conditions of a founded structure, just require regional adjustments, which are already available [19]. Comparison of settlement values, measured for almost 50 structures, with those obtained by dilatometer-based calculations is presented in Fig. 9, and it shows sufficiently high correlation (R^2 = 0,92). The analysed set of structures composed mostly of buildings with shallow foundations.

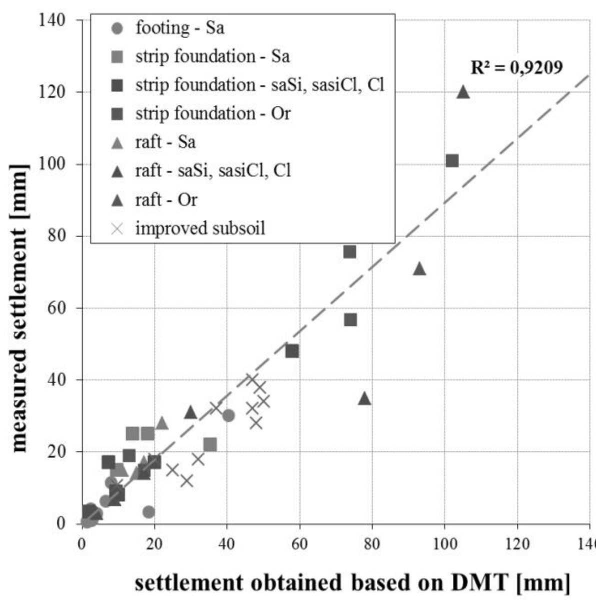

Fig. 9. Calibration curve obtained for Polish conditions relating to measurements from literature [19].

In the case of founding an embankment on very soft or organic soils, in which the quality of drilling and collected samples is often insufficient, only in situ probing allows for obtaining reliable parameters for design calculations. Currently, when such soils are present, geotechnical investigators often describe these strata as non-bearing and do not conduct additional tests to verify their strength and deformation parameters. This approach, all too often, results in over-conservative design solutions due to lack of detailed characterisation and high level of uncertainty in the design assumptions. Proper investigation may provide enough information to optimise the design without the decrease in reliability.

Furthermore, due to dynamic character of the traffic load, geophysical methods allowing for assessment of a continuous profiles, should be used as well. Especially those which allow for qualitative and quantitative assessment, as well as estimation of dynamic stiffness of the subsoil, should be preferred. These methods include: Cross-Hole, SDMT, SCPTu, and CSWS/SASW. Dynamic stiffness can also be assessed in the laboratory with the use of Bender Element Test (BET).

However, application of the state-of-the-art methods alone may not be sufficient for obtaining reliable results. Certified and accredited subcontractors should be responsible for geotechnical investigations, and the equipment should be regularly checked and calibrated. As much importance should be given to the qualifications and experience of the personnel conducting *in-situ* and laboratory tests, as well.

7 Conclusions

Some of the basic requirements and challenges associated with the design of railway embankments were presented in the paper. With the increase in funding provided for railway investments by the European Union, as well as the need to ensure the interoperability of railway infrastructure, adoption of the harmonized European standards plays an important role. However, some challenges are still present in regard to required reliability levels and factors that affect the selection of design solutions. These include mainly railway traffic loads, influence of the geometry and its changes, as well as the scope and quality of geotechnical investigation and obtained ground parameters. Generally, requirements currently used in Polish railway industry tend to be over-conservative in regard to expected level of safety as well as the loading conditions.

The differentiation of expected reliability level for new and existing lines, even when expressed by global safety factors, is hard to justify. Especially, when modernization of existing lines is considered, this results not only in the necessity of increasing the safety levels due to increased loading if speed of the line is increased, but also due to the fact that the construction itself is conducted. The discrepancy in the second factor, the railway traffic loads, is now a subject of concern during the works on the evolution of the Eurocodes (second generation planned for implementation in 2024) which may lead to changes in the Eurocode 1.

Finally, significant attention should be paid to the quality of the geotechnical investigation as it has a direct impact on the reliability of the design. Low quality of the investigation and uncertainty in the parameters estimation may result in over-conservative assumptions of designers, who are responsible, and by law personally liable, for the effects of their design assumptions.

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