RIGA TECHNICAL UNIVERSITY

Endijs Virsis

METHOD FOR MODELLING THE BEARING CAPACITY OF ROAD STRUCTURE

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on 8th December 2023, at 12.15 at the Faculty of Civil Engineering of Riga Technical University, Kipsalas Street 6A, Room 342.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Endijs Virsis ……………………………. (signature)
Datums: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction; 5 chapters, Conclusions, 78 figures, and 13 tables; the total number of pages is 123. The Bibliography contains 79 titles.

CONTENTS

1. INTRODUCTION

1.1. Importance of the topic

In Latvia, significant funding for the road sector came from the European Union's Structural Funds, but from 2018, it has decreased from EUR 124 million to EUR 63.2 million in 2019. It means that in the coming years, road construction and renovation will become increasingly dependent on the state budget. Europe has defined the goals for the next period, which do not include road construction and similar projects.

In recent years, because of decreasing road sector funding, the number of pavement reinforcement projects has increased significantly. At the beginning of the project, the condition of the existing road is evaluated, taking into account various pavement evaluation criteria, and it is determined in which sections of the road it is possible to strengthen the pavement and where a complete reconstruction of the structure is required. In Latvia, pavement construction is designed using "Recommendations for Road Design. Road Construction". By not envisaging a complete pavement construction, it is possible to reduce the project costs significantly. Thus, it is possible to optimize the available funds for road reconstruction. To perform a high-quality road construction reinforcement project, it is very important to analyse the load-bearing capacity and structural condition of the existing road structure and foundations with the help of geotechnical or other research. Incorrect assessment of the existing foundation structure properties and residual load-bearing capacity can create significant risks of structural deformations in the new road structure. As a result, the road may lose load-bearing capacity and incur unforeseen costs.

Soil with weak bearing capacity, like peat and organic grounds, is widespread in Latvia. Most of our national road network is built on this type of soil. During the design of roads and the geotechnical investigation, when weak bearing capacity soils are detected, the civil engineer may encounter many problems that can delay the project development process. It may be necessary to contact the customer of the particular object and jointly try to find the most advantageous, rational, economical and safest solution for road users.

The simplest, but certainly not the cheapest, solution is to replace the soil with weak load-bearing capacity, which is also expected in most projects because civil engineers lack the experience and knowledge to offer alternative solutions. In most of Europe and other countries, where sedimentary rocks of similar origin and soils of weak bearing capacity are common, geotechnical design is carried out. For civil engineers in Latvia to be able to perform geotechnical design, it is necessary to educate designers in the relevant field.

1.2. Aim of the Doctoral Thesis

The doctoral thesis aims to develop a calculation method for modelling the bearing capacity of road structures using the properties of soil layers and other materials, as well as to develop a transport load model to be used for performing road geotechnical calculations and developing project solutions.

1.3. Tasks of the Doctoral Thesis

1. To collect information about geotechnical strengthening methods of highway construction used in Latvia and elsewhere worldwide.
2. To evaluate the static plate test results obtained during the geotechnical investigation and construction of the object. To perform the analysis of the obtained data by determining the mutual correlation of the results and the factors that affect the accuracy of the obtained results.
3. To develop a finite element calculation model, with the help of which it is possible to determine the bearing capacity and compaction of the road structure.
4. Considering the results of the static plate test obtained during the geotechnical investigation and performing the final element calculations, it is planned to develop an analytical calculation formula for evaluating the bearing capacity of the road structure.
5. To gather information on geotechnical field research methods and make a mutual comparison. Analyse the interpretations of the obtained data and evaluate their use for geotechnical calculations.
6. To develop a transport load model that would reflect the real impact of traffic load on the road structure and which can be used for geotechnical calculations and development of project solutions.

1.4. Research results presented for the Thesis defence

1. Analysis and comparison of the parameter values of soil layers interpreted by geotechnical research field test methods, according to Latvian soil conditions, using calculation formulas developed in foreign studies to determine the physical and mechanical properties of soil layers.
2. The developed traffic load model needs to be applied when performing geotechnical calculations of road construction (slope stability check, road global stability, etc.).
3. Using a finite element calculation model and DMT, CPT research data interpretations developed static plate test simulation method for modeling the bearing capacity of road structure.
4. The developed analytical calculation formula for determining the bearing capacity of the existing foundation/ground surface (Ev_2) using geotechnical survey data.
5. The developed block diagram for the analysis of the geotechnical situation of the highway, the development of project solutions and the determination of the necessary inspections.

1.5. Scientific innovation of the research

1. A new traffic load model has been developed, which needs to be applied when performing geotechnical calculations of road construction (slope stability check, road global stability, etc.).

2. An innovative static plate test simulation method has been developed for modelling the bearing capacity of a road structure using the finite element calculation model and interpretations of DMT (dilatometric test) and CPT (cone penetration test) research data.
3. A new analytical calculation formula was developed for determining the bearing capacity of the existing foundation/ground surface (Ev_2) using geotechnical survey data.
4. An original block diagram has been developed for the analysis of the geotechnical situation of the road, the development of project solutions, and the necessary inspections.

1.6. Practical significance of the research

the accuracy of the interpretations of soil layer parameters of geotechnical research field test methods have been analysed, compared and determined according to Latvian soil conditions, using calculation formulas developed in foreign studies for determining the physical and mechanical properties of soil layers.

A traffic load model has been developed, which needs to be applied when performing geotechnical calculations of road construction (slope stability check, road global stability, etc.).

A static plate test simulation method has been developed for modeling the bearing capacity of a road structure using the finite element calculation model and interpretations of DMT, and CPT research data.

An analytical calculation formula has been developed for determining the bearing capacity of the existing foundation/ground surface (Ev_2) using geotechnical survey data.

A block diagram has been developed for the analysis of the geotechnical situation of the road, the development of project solutions and the necessary inspections.

1.7. Thesis structure

The dissertation consists of six chapters.

Chapter 1 explains the topicality of the subject, defines the purpose of the work and the tasks to be solved, as well as formulates the research results proposed for defence, the scientific novelty and practical value of the work.

Chapter 2 contains information on the progress of highway design, as well as the analysis of the initial data. A block diagram has been developed, with the help of which it is possible to control the design progress and simply follow the progress of the project development and the actions to be performed. Chapter 2 describes how to accurately perform geotechnical survey data analysis and which are the most important parameters of the soil layers to pay attention to in order to determine whether the soil on the surface of the earth is of appropriate quality and bearing capacity.

Chapter 3 contains information on the methods of geotechnical strengthening of road construction. The chapter presents the classification of construction solutions on low bearing capacity soil. An evaluation of geotechnical design methods was carried out, describing the advantages and disadvantages of each solution. An insight into the methods used in Latvian road construction projects is provided.

Chapter 4 summarizes the geotechnical investigation data of several construction/design objects. Data interpretation and analysis of the obtained results were conducted at research points where several field test research methods were duplicated. The results have been compared with laboratory test data and the calculation models have been developed, determining how significant the choice of a different geotechnical research method has on project solutions.

Chapter 5 analyses the traffic load models adopted by different countries for the design of roads and bridges. Considering the heavy vehicle typical in Latvia and elsewhere in the world, which has the greatest impact on road construction, a traffic load model has been developed, with the help of which geotechnical solutions should be developed.

Capter 6 analyses the data of the static slab test, determining the most important factors that affect the accuracy of the tests performed during the geotechnical investigation. A static slab test simulation method has been developed to model the bearing capacity of a highway structure using the finite element calculation model and interpretations of DMT and CPT research data. Taking into account the data from the geotechnical investigation and the final element calculations, an analytical calculation formula was developed to determine the bearing capacity of the existing base/ground surface (Ev2) using the geotechnical investigation data.

1.8. Approbation in conferences

- 30th International Baltic Road Conference, September 24–25, 2021, Riga, Latvia.
- Riga Technical University 62nd International Scientific Conference, October 28, 2021, Riga, Latvia.
- 5th International Conference "Innovative Materials, Structures and Technologies", September 28–30, 2022, Riga, Latvia.
- 12th International Conference "Environmental Engineering", April 27–28, 2023, Vilnius, Lithuania. List of publications developed during doctoral studies
- Virsis, E., Paeglītis, A., Zarins, A. (2020) Road Design on Low Bearing Capacity Soils. *The Baltic Journal of Roads and Bridge Engineering,* Vol. 15, No. 3, pp. 19–33. https://doi.org/10.7250/bjrbe.2020-15.481
- Virsis, E., Paeglītis, A., Jateikienė, L. (2023) Analysis of physical and mechanical soil properties determined using interpretations of dilatometric test (DMT) and cone penetration test (CPT) methods. *The Baltic Journal of Roads and Bridge Engineering, 2023,* Vol. 18, Iss. 2, pp. 223–250. https://doi.org/10.7250/bjrbe.2023-18.605
- Virsis, E., Paeglītis, A., Zarins, A. (2021) Evaluation of the Residual Load-Bearing Capacity of the Existing Road Using Plate Loading Test. *IOP Conference Series: Materials Science and Engineering,* Vol. 1202, Article 012012. DOI:10.1088/1757-899X/1202/1/012012
- Virsis, E., Paeglītis, A., Zarins, A. (2023) Development of a Static Plate Test Finite Element Calculation Model. *Journal of Physics: Conference Series*, Vol. 2423, Article 012039. DOI: 10.1088/1742-6596/2423/1/012039

- Virsis, E., Paeglītis, A. (2023) Analysis of physical and mechanical soil properties determined using probing data interpretations. *12th International Conference "Environmental Engineering",* (accepted for publishing). eISBN 978-609-476-342-7. https://doi.org/10.3846/enviro.2023.877

2. ANALYSIS OF GEOTECHNICAL RESEARCH DATA AND DEVELOPMENT OF PROJECT SOLUTIONS

2.1. Assessment of the road section and development of necessary solutions

Considering that the geological situation under the road construction is very variable, there is a possibility that sections of soil types of different strength, composition and consistency are found within the framework of one design and construction object. In order to make it easier to follow the necessary actions during the development of the project, a block diagram was developed in the Doctoral Thesis, see Fig. 2.1.

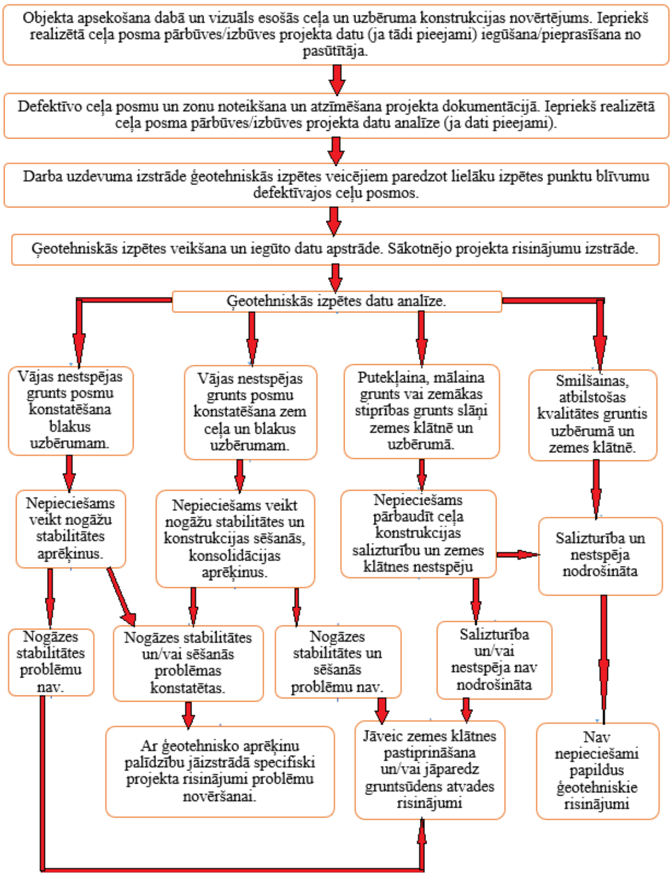

Fig. 2.1. Block diagram of road project solution development.

2.2. Analysis of geotechnical survey data

Geotechnical drilling and probing are necessary for determining the soil composition, taking soil samples for laboratory analysis, determining the groundwater level and specifying the boundaries of the soil layers. Drilling works are mainly performed with the help of a drilling machine; a manual drilling tool is rarely used. Dynamic and static probing equipment, a dilatometer, and other research methods are used for probing works and determining the physical and mechanical properties of soil layers.

2.2.1. Sandy soil of appropriate quality in the embankment (dam) and at the base

In sections of the road where the analysis of geotechnical survey data has determined sandy soils, the conditions are adequate, and no foundation reinforcement is required. On sandy soils, the bearing capacity requirements $Ev_2 \geq 45$ MPa are usually achieved on the surface of the ground, and this type of soil is also frost-resistant, so there is no need to worry about the impact of frost on the road structure.

2.2.2. Dusty, clayey soil or layers of lower strength in the subgrade and embankment

The parameters of clayey soils vary depending on the moisture content. The closer the moisture content of the soil layer is in its natural state to the flowing point, the lower the resistance of the soil to the load caused by self-weight and traffic. Flowing, clayey soils can be considered as layers of weak load-bearing capacity; therefore, when such soils are found with a sufficiently large total thickness of the layer, it is necessary to perform geotechnical calculations of slope stability and structural settlement.

2.2.3. Soil layers of weak bearing capacity in the subgrade and embankment

Soils of weak bearing capacity are those which cannot achieve a bearing capacity of 25 MPa for the lower layers of the subgrade. These are generally plastic or flowable soils with high fines, increased moisture content and a high percentage of organic particles.

Soils with weak bearing capacity are often located deeper than the surface of the designed ground cover, and their excavation is not always technically possible or does not provide the desired economic effect. In such cases, it is necessary to carry out geotechnical calculations of the road, determining how much influence the soil layers of weak load-bearing capacity have on the structure, and solutions for strengthening the subgrade should be planned and developed.

2.3. Development of project solutions and calculations to ensure the longevity of the structure

All embankments must be designed and constructed in such a way that they are stable and provide a sufficient margin of safety against the loss of the load-bearing capacity of the structural foundations and the stability of the slopes. Slope slip mostly occurs along the slip surface, which is usually arc-shaped, and the lower part of which passes through a layer of soil of weak bearing capacity because it cannot provide the necessary shear resistance. Settlement and consolidation of the structure occur as a result of compaction of soil layers.

Various stability analysis programs are available for performing geotechnical calculations, and simplified calculations can be performed analytically using calculation formulas developed in research.

3. METHODS FOR GEOTECHNICAL REINFORCEMENT OF HIGHWAY STRUCTURES

The main function of the road structure is to transfer the traffic load to the ground/subgrade on which it rests. A correctly assessed existing foundation and a properly developed structural solution transfer the load caused by the traffic and the road's self-weight into the deeper soil layers without overloading them. Overloading the soil can lead to immediate settlement and consolidation or shear failure, which can cause structural deformations. Thus, geotechnical, construction and design engineers must evaluate the bearing capacity of the soil during the development of the project.

3.1. Road design on low bearing capacity soils

Construction over low bearing capacity soil can essentially be subdivided into five broad classifications:

1. Rerouting (changing the position of the road without crossing weak load-bearing soils).
2. Excavation of weak soil (soil layers of weak bearing capacity are excavated, and the road structure is built in the trench).
3. Replacement (soil with weak bearing capacity is excavated and replaced with frost-resistant material).
4. Displacement (soils of weak bearing capacity are pushed to the side with using various methods).
5. Soil left in place (geotechnical design providing special solutions and/or materials to reduce the impact of transport loads on soil layers with weak bearing capacity).

Excavation is the safest, but not the most economical, solution to cross a section of soil with weak bearing capacity or strengthen the structure of an existing road.

Methods that leave weak soils in place to avoid extensive earthworks are becoming more common as more cost-effective solutions are sought as road construction budgets shrink (see Fig. 3.1).

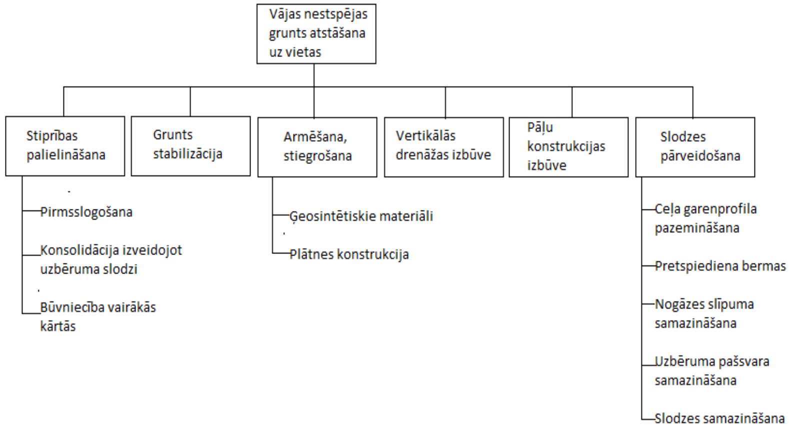

Fig. 3.1. Methods that leave weak bearing capacity soils in place.

3.2. Evaluation of road geotechnical design methods

The selection of a proper solution for the construction or improvement of a road over weak soil is usually based on rational considerations, such as acceptable budget and other resources, and the performance requirements set for the new structure. For a road design engineer, the most important thing is to correctly identify the causes, problems and factors that could affect the bearing capacity and stability of the road.

3.3. Experience of soil reinforcement methods in Latvia

Until 2019, there have been no recommendations, specifications or manuals in Latvia that summarize and describe the methods of soil consolidation, for example, road embankments over pile foundations, vertical drainage soil consolidation, ground piles under the embankment, etc., solutions in cases where road structure is designed over sections with poor bearing capacity. Then, the structure cannot provide sufficient support in its natural way to ensure the necessary road surface stability throughout its intended lifetime. Thus, each designer is guided by their own experience, knowledge, prejudices and safety concepts, which creates the risk that irrational and unnecessarily expensive solutions can be developed or perhaps cheap solutions that do not meet specific needs.

3.3.1. Experience in soil excavation and replacement

In Latvia, until 2018, in the design of roads, as the main and mostly the only option for strengthening the subgrade, an exchange of soil with weak bearing capacity was used. Such construction technology is expensive, time-consuming and consumes many resources.

3.3.2. Pile columns

In the 2018 season, the two sections of the national regional motorway *Augšlīgatne–Skrīveri* (P32) (47.20–60.29 km and 61.27–71.27 km) had the most extensive road repairs within the national road network. During the reconstruction of the road 49.50–50.00 km, weak bearing capacity soil – a bog section with a peat layer at a depth of 10 m – was determined. This was revealed by additional research; the designer suggested possible solutions for soil stabilization.

To stabilize the soil, a method of constructing combined columns and pile columns were used for the first time in the national road network. 30 cm wide and up to 6 m long concrete columns were built, and above them, 60 cm wide up to 2 m long gravel/crushed columns. A total of 952 columns were constructed, arranged in a 2.5 m × 2.0 m grid. A team of specialists from Poland came to Latvia to engage in the construction works.

3.3.3. Crushed stone stabilization berm construction

In 2019, the consequences of the road deformations on *Peldu* Street were eliminated, and technical solutions for conservation were developed. The condition of the road structure was assessed as critical. Slippage of the road structure due to the *Gauja* water, groundwater and other factors made allowing vehicles to drive along *Peldu* Street dangerous. During the pavement structure monitoring, it was found that the deformations progressed over time, and the crack width increased (see Fig. 3.2). To prevent a complete collapse of the road structure and to restore the movement of the transport, it was necessary to prevent the development of deformations.

Fig. 3.2. Deformations of *Peldu* street road structure.

Several slope and road reinforcement options were developed for technical conservation solutions. One of the main factors of the project was the limited time to complete the construction works and to restore the traffic on *Peldu* Street. Due to the limited construction time, the main solution was constructing mineral berm and wrapping road construction layers in high-strength geotextiles.

3.3.4. Gabion wall construction

On the A2 motorway between Riga and Sigulda in 2019, in the area above the *Rauna* River, the longitudinal profile of the road was raised, and the embankment slopes reinforced with gabion support walls.

The existing embankment was constructed of moraine loam (geological survey has a bond Cu = 20 kPa), so there would be a high risk of slope slipping and soil crushing if the vertical load was increased by the additional embankment. The problem was solved with the help of soil anchors (see Fig. 3.3), which served to keep the old embankment body from slipping and falling.

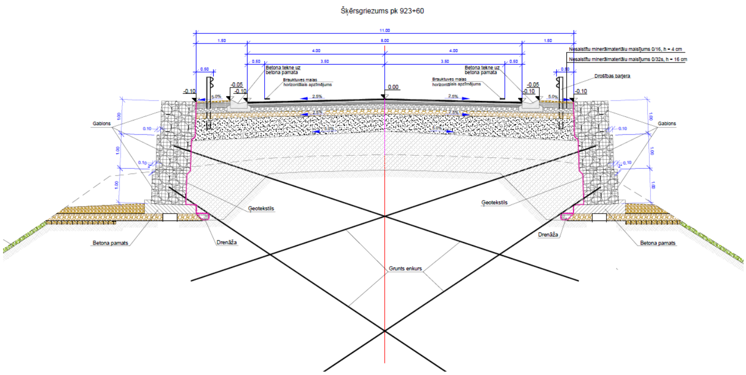

Fig. 3.3. Project solution for National Motorway A2.

4. PHYSICO-MECHANICAL PROPERTIES OF SOIL LAYERS

Geological field exploratory tests can provide several advantages over the traditional drilling, sampling and laboratory testing approach used in many projects. However, like all tests, field research tests also have several limitations that must be considered, as each research gives slightly different interpretation values.

4.1. Review of studies conducted

Several studies have been performed in recent years comparing the correlations between cone penetration test, Marchetti dilatometer test, and dynamic penetration test.

Krzysztof Nepelski analysed the building – subsoil interaction in 2019. He concluded that DMT test interpretations showed higher constrained modulus of soil layers than CPT test interpretations. The same conclusion was made by Alexandru Poenaru in 2016. The results of his investigation determined that DMT showed a stiffer response of the soil compared with the values obtained by laboratory investigations and CPT interpretations. McNulty and Harney concluded that the DMT test method, rather than the CPT, should be used to estimate the finite deformation modulus of subsoil layers and be used for structural settlement analyses.

Mensur Mulabdic,, in his research, compared CPT and DMT test interpretation results. He concluded that CPT and DMT tests showed remarkable repeatability and proved to be a valuable aid in characterising embankment quality in terms of inhomogeneity and physical and mechanical properties. In his investigation, he determined that the modulus of vertical constrained deformation from the oedometer (on submerged specimens) was much smaller than that from CPT interpretation or even lower if compared to DMT standard interpretation values (performed on clay layers that were not submerged).

In early 2022, a study on the correlation between CPT and DMT tests was published. It was determined that the general overlap of the constrained modulus was better at lower OCR values and in homogeneous soil intervals. In soil intervals with higher OCR values, the DMT test showed higher constrained modulus values. Miguel Angel Benz-Navarrete developed a linear model to predict the qc (CPT) values from the measurements of qd made with Panda (DCP). This model is reliable if skin friction along the rods is not detected during the test.

Considering all previous research and the relationship of small numbers of studies on the intercorrelations of DCP and other research methods, it is clear that there are still many unknowns affecting the physical and mechanical soil properties determined using interpretations of DMT, CPT, and DCP methods.

4.2. Description of the field research test

4.2.1. Static cone penetration test method

The cone penetration test is a method used to determine the geotechnical engineering properties of soils and delineating soil stratigraphy. It was initially developed in the 1950s at the Dutch Laboratory for Soil Mechanics in Delft to investigate soft soils. The cone penetration test has become internationally one of the most widely used and accepted test methods for determining geotechnical soil properties.

In 1983, Robertson and Campanella published two major papers on interpreting the CPT. Since 1983, there have been several major publications on the interpretation of the CPT. Table 4.1 shows the perceived applicability of the CPTU to estimate soil parameters.

Table 4.1

Perceived Applicability of CPTU for Deriving Soil Parameters

Soil Type	D_r	ψ	K_0	*OCR*	S_t	C_u	Φ	*E*, *G*	*M*	G_0	*k*	C_h
Sand	2–3	2–3		5			2–3	3–4		2–3	3	3–4
Clay			2	1	2	1–2	4	3–4	4	3–4	2–3	2–3

1 – high; 2 – high to moderate; 3 – moderate; 4 – moderate to low; 5 – low reliability; Blank – no applicability;,

D_r – relative density;
Ψ – state parameter;
OCR – over consolidation ratio;
C_u – undrained shear strength;
C_h – coefficient of consolidation;
E, *G* – Young's and shear moduli;
G_0 – small strain shear moduli;
φ – friction angle;
K_0 – in-situ stress ratio;
M (or mv) – compressibility;
S_t – sensitivity;
k – permeability.

One of the main applications of CPT is the profiling of soil layers and the determination of soil type.

4.2.2. DMT (dilatometric test) method

The flat dilatometer test is an in-situ testing method used to determine the strength and deformation characteristics of fine-grained soils. The test is performed using a dilatometric, which operates on the principle of verification of values by using the displacements of the inductive sensors (with a sensitivity of up to 0.001 mm). The advantage of these tests is a more accurate description of the displacement and deformation of foundation soil. The corrected DMT results are used to obtain information on soil stratigraphy, in-situ state of stress, shear strength and deformation properties.

4.2.3. Dynamic penetrometer test

The dynamic cone penetration test (DCP) was developed by Scala (1956). The current model was developed by the Transvaal Roads Department in South Africa. The mechanics of the DCP shows features of both the CPT and SPT. The DCP is performed by dropping a hammer from a certain fall height, measuring penetration depth per blow for a certain depth. Therefore, it is quite similar to the procedure of obtaining the blow count N using the soil sampler in the SPT. In the DCP, however, a cone is used to obtain the penetration depth instead of the split spoon soil sampler. In this respect, there is some resemblance with the CPT in that both tests create a cavity during penetration and generate a cavity expansion resistance.

4.3. Comparison of CPT and DMT using geotechnical investigation data of road P32

A geotechnical investigation was performed on the Latvian regional road P32 *Augšlīgatne–Skrīveri* 49.58–49.97 km section. In the section 49.66–49.93, under the road and next to the road embankment, organic sediments were detected – peat and sludge. The thickness of the layer of organic sediments under the road embankment in the mentioned section was uneven and varied within 0.9–5.7 m, on average – 3.0 m.

4.3.1. The interpretations of the results obtained in the study point 497 + 20D

The interpretations of the results obtained in the first study point (497 + 20D) are summarized and plotted to make the comparison of soil parameters easy to understand (see Fig. 4.1). Various correlations and formulas have been developed for expressing CPT and DMT data in physical and mechanical parameters. Soils are divided into soil types. Initially, the type of soil and the thickness of the layers are determined from the obtained probe parameters. Different correlations and formulas have been developed for each soil type; therefore, it is important to accurately determine the soil type.

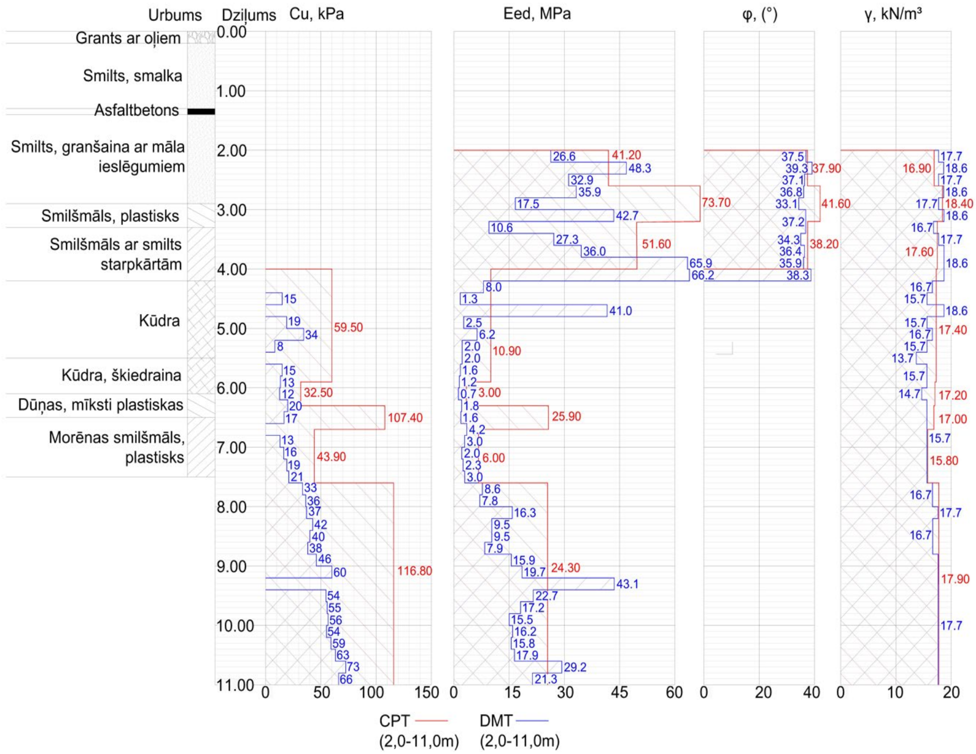

Fig. 4.1. Physico-mechanical properties of soil layers at research point 497 + 20D.

Comparing the obtained results, it can be seen that the research of the static probe (CPT) shows higher strength values in all the considered positions. Comparing the results of CPT and

DMT, CPT shows, on average, an 8 % higher value of friction angle and 87 % higher value of constrained deformation modulus in sand soils, 130 % higher undrained shear strength and 60 % higher value of constrained deformation modulus in clayey soils, 300 % higher undrained shear strength and 360 % higher value of constrained deformation modulus in low bearing capacity soils (peat, organic layers).

4.3.2. The interpretations of the results obtained in the study point 498 + 40D

In the second point (498 + 40D), comparing the results of CPT and DMT, CPT shows on average 8 % higher value of friction angle and 200 % higher value of constrained deformation modulus in loose sand, 9 % higher value of friction angle and 90 % higher value of constrained deformation modulus in dense sand, 230 % higher undrained shear strength and 185 % higher value of constrained deformation modulus in low baring capacity soils (peat, organic layers).

4.3.3. Slope stability calculations using interpreted values

Slope stability and construction settlement were calculated using the soil parameters obtained by the CPT and DMT methods, and the difference between the calculation results was compared. The results of the first calculation using the CPT interpretation at study point 497+20D are shown in the graph (see Fig. 4.2).

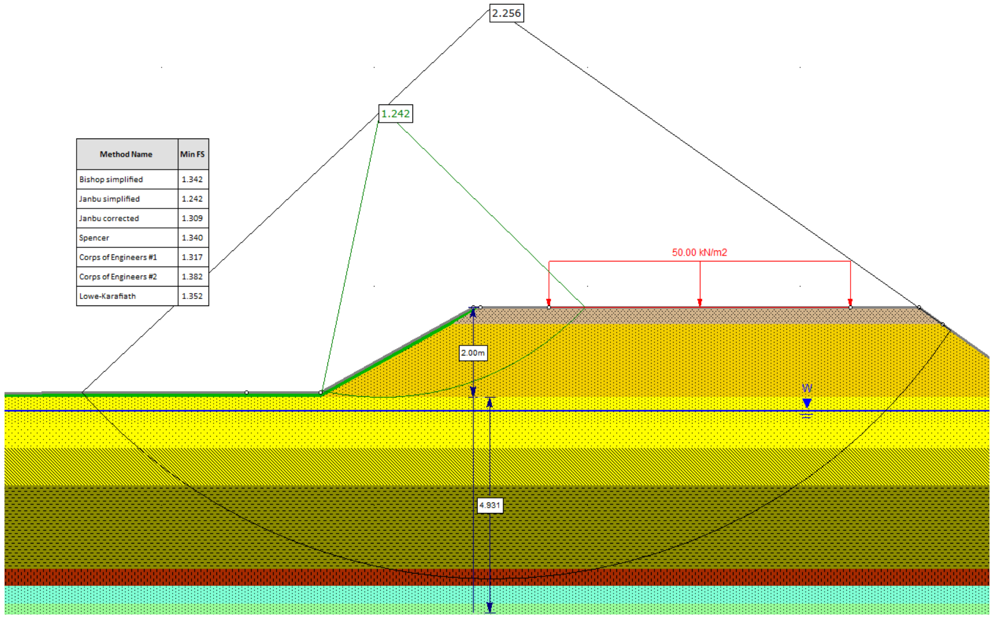

Fig. 4.2. Slope stability calculation results using CPT soil parameter interpretations at investigation point 497+20D.

Safety factors for slope stability are summarized in Table 4.2.

Table 4.2

Safety Factors for Slope Stability

Calculation based on properties of	Slip surface location	Factor of safety						
		Bishop simplified	Corps of Engineers #1	Corps of Engineers #2	Janbu simplified	Janbu corrected	Lowe-Karafiath	Spencer
CPT 497 + 20D	Directly on the roadside	1.342	1.317	1.382	1.242	1.309	1.352	1.340
DMT 497 + 20D		1.504	1.471	1.572	1.398	1.473	1.528	1.494
CPT 497 + 20D	Under entire carriageway structure	2.374	2.409	2.624	2.256	2.436	2.329	2.372
DMT 497 + 20D		1.073	1.160	1.141	1.073	1.159	1.094	1.070
CPT 498 + 40D	Directly on the roadside	1.342	1.317	1.385	1.225	1.303	1.352	1.34
DMT 498 + 40D		1.511	1.478	1.581	1.404	1.479	1.536	1.500
CPT 498 + 40D	Under entire carriageway structure	2.517	2.482	2.535	2.136	2.325	2.345	2.509
DMT 498 + 40D		1.336	1.414	1.407	1.247	1.354	1.356	1.353

Both DMT calculations further confirm that the existing soil layers are highly compressible. Judging by the results of the calculations, it can be concluded that by defining the soil parameters for each 20 cm thick layer, the existing properties of the soil layers can be represented more accurately. The soil layers are non-homogeneous, so the properties can vary significantly within the same soil type.

4.3.4. Construction settlement calculations using interpreted values

According to the results of the calculations, the most significant deformation occurs in the layers of peat, sludge and flowing loam (see Fig. 4.3) because the constrained deformation modulus of these layers has the lowest values.

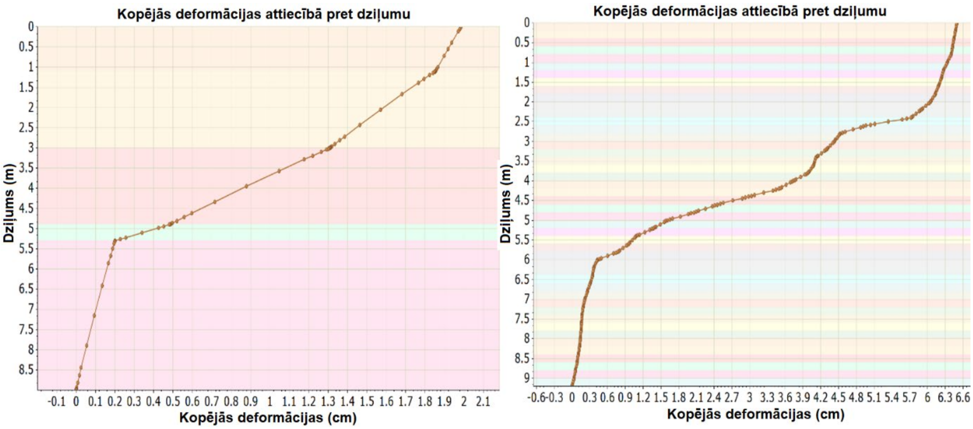

Fig. 4.3. Construction settlement results using soil parameter interpretations at investigation point 498 + 40D: CPT (left); DMT (right).

The settlement of the structure is determined to be 1.99 cm from CPT data and 6.50 cm from DMT data. 90% of the total deformation of the structure occurs in the range from 2.0 m to 5.5 m. The difference between the results obtained is 4.51 cm or approximately 3.25 times. Given that we have previously determined that deformation values for the DMT study coincided with the results of the consolidation tests (6 test samples), it can be concluded that the calculation with the CPT test data gives a more optimistic structural settling result than actually expected.

The physico-mechanical properties of the average soil layers do not allow to evaluate the strength changes within one soil layer. The determined amount of deformation and the results of other geotechnical calculations can differ significantly when using the average values of the layers or, on the other hand, using the properties for each 20 cm thick soil layer. The amount of deformation increases significantly in soil layers with very low physico-mechanical properties; therefore, inaccuracies may occur when using average values. Within one soil type, layers of higher strength alternate with intermediate layers of lower bearing capacity, as a result of which the average parameters of the soil layer show low, but not critical values.

4.4. Comparison of CPT, DMT, and DCP test methods using road P86 geotechnical investigation data

4.4.1. Interpretations of the obtained results

At the research point, which is located at the 34.46 kilometre of the road, all three probing research methods were performed. According to the borehole data, it was determined that there is a 1.1-meter-thick layer of peat under the road.

Comparing the obtained results (Fig. 4.4), it can be seen that the static probe (CPT) study shows higher property values – about 10 times higher strength than DCP and up to 3 times higher strength than DMT. According to CPT data, fine sand of appropriate quality has been determined up to a depth of 4 metres; however, evaluating the interpretations of DMT and DCP, it can be concluded that both other research methods have determined lower quality soil layers starting from a depth of 1.5 m.

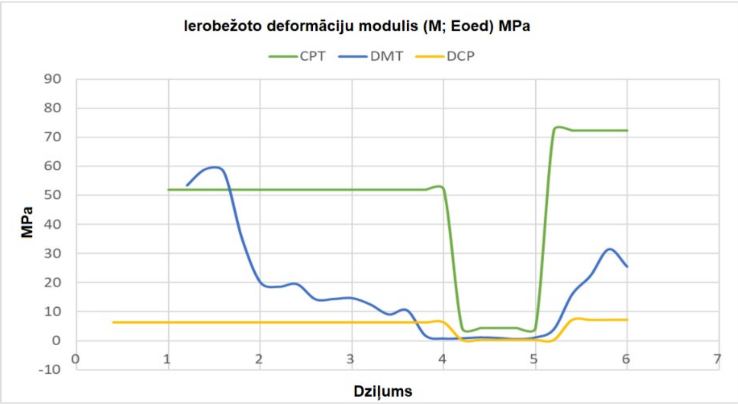

Fig. 4.4. Changes in the values of the constrained deformation modulus (34.46 km).

A significant decrease in the strength of the limited deformation modulus in the peat layer has been found for all three research methods. Peat is a soil with weak load-bearing capacity; if its potential impact due to cyclic transport load is not properly evaluated, it can cause significant deformations in the road structure.

In order to compare the impact of the differences in the obtained deformation moduli on the road structure, a settlement calculation was performed, see Fig. 4.5.

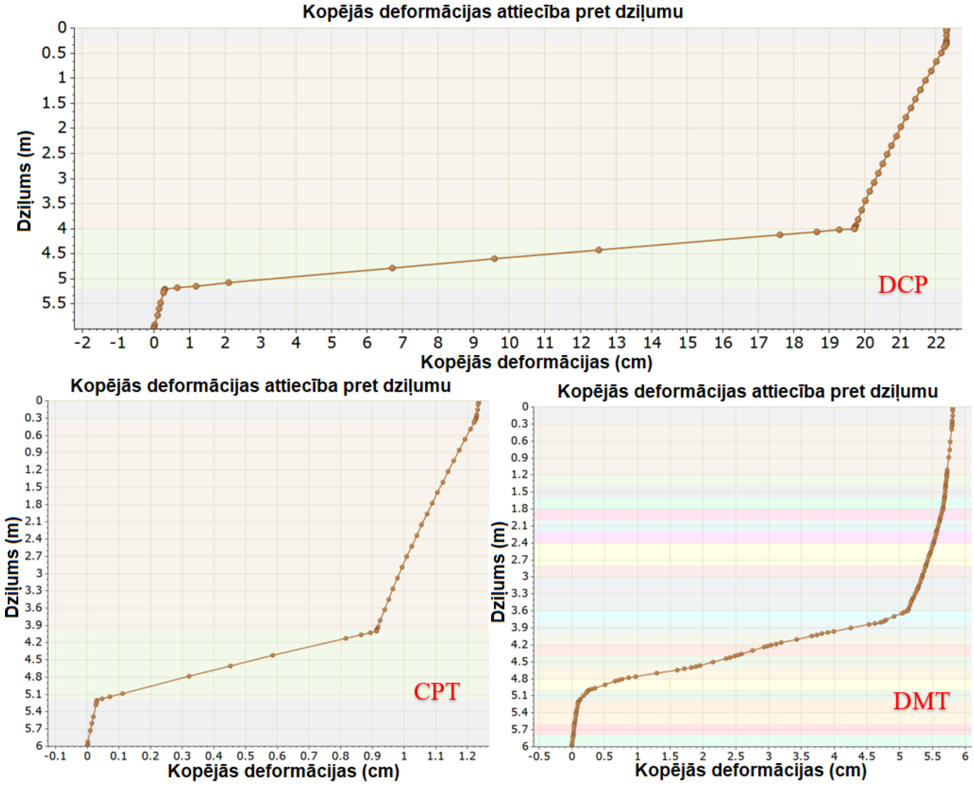

Fig. 4.5. Structural deformation results (34.46 km).

According to the obtained calculation results, the largest deformation occurred in the peat layer, at a depth of 4.00 to 5.20 meters, because the deformation modulus of this layer was the lowest. Structural deformations using CPT data were calculated as 1.23 cm, using DMT data as 5.80 cm, and using DCP data as 22.20 cm. 90 % of the total structural deformations occur in the range of 4.0 m to 5.2 m. The differences in the obtained results are significant, for example, when comparing the CPT and DCP deformations, the differences are 21 cm in size. If the development of the project would be carried out based on the data of the static probing, then the development of additional solutions for strengthening the subgrade/road base would not be necessary; but in accordance with the results of the dynamic probing, significant work should be carried out to improve the bearing capacity of the subgrade/road base.

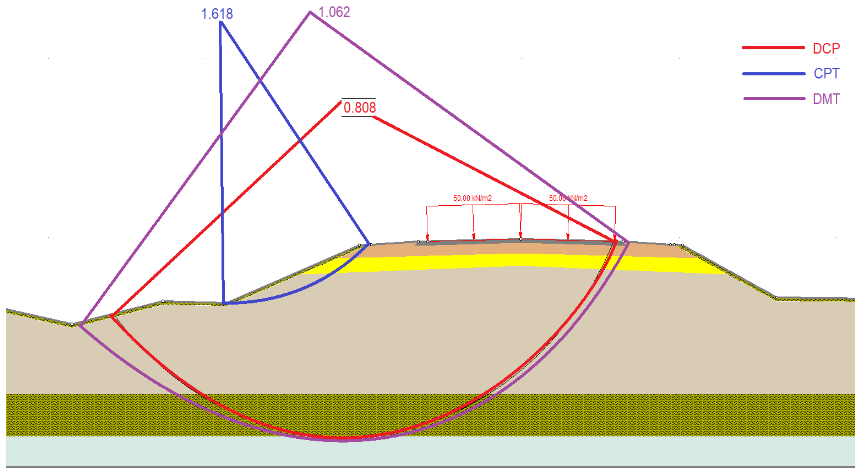

Fig. 4.6. Results of slope stability calculations (34.46 km).

When making calculations using the data of the static probing test, it was determined that the longevity of the road will be ensured when the complete road structure is built, and the peat layer does not have an adverse effect on the bearing capacity of the road structure. The settlement calculation using DMT interpretations determined deformations in the amount of 5.8 cm; however, it was concluded that the stability of the slopes is ensured. Taking into consideration that 5.8 cm deformations can create significant risks for the serviceability of the structure, it is necessary to develop solutions for strengthening the ground surface, which will increase the construction costs. Calculation results using DCP interpretations showed significant problems to ensure the serviceability of the road structure. The deformation of the weak bearing capacity soil layer under the load was determined to be 19 cm, and the slope stability safety factor showed that when the full road structure is built, the road structure is expected to slip. When developing project solutions using DCP data, construction costs are significantly increased, and complex constructive solutions are required to limit the development of deformations in soil layers with weak bearing capacity. Considering that approximately 60– 90% of the total structural settlement develops in the soil layer of weak bearing capacity, the greatest impact on the results of the calculations was caused by the differences in interpretations of the soil layer of weak bearing capacity.

4.5.Comparison of CPT, DMT, and DCP test methods by analysing field studies.

Analysing the interpretation data, it was concluded that the static cone penetration test (CPT) method showed the highest average values of the constrained modulus and undrained shear resistance of the soil layers at all research points.

The static cone penetration test (CPT) method interpretations determined better soil parameters than they actually are. In order to avoid such problems in the course of project development, it is necessary to carry out laboratory tests in addition to probing, to verify the obtained results of interpretations and, if necessary, perform data correction.

The CPT test data interpretations give a more optimistic structural settling result and more optimistic slope stability than actually expected. This may create the risk of unexpected structural deformations occurring after the completion of the construction works, which could not be determined by calculations due to the imprecisely determined properties of the soil layers.

The dynamic probe method showed the lowest interpretations of soil parameters, as well as the largest settlement deformations and the greatest slope stability problems. Geotechnical solutions developed based on the DCP interpretations provide greater structural safety compared to the CPT and DMT, but also increase construction costs.

The interpreted soil layer parameter values using the DMT method were equivalent and only slightly different from the laboratory data. Therefore, we can conclude that the DMT method provided the most accurate initial data for calculations. The CPT method also showed good soil properties, while the DCP method gave conservative data.

Vertical structural deformations are closely related to slope stability. At the research points where the largest amount of settlement was determined, the stability of the slopes was not ensured.

5. TRAFFIC LOAD MODEL FOR GEOTECHNICAL DESIGN OF ROAD STRUCTURES

The assumed traffic load is a characteristic quantity about which there is no consensus among designers; unlike bridge design, where load combinations are defined, geotechnical calculations do not define the traffic load that should be used for calculations. When developing geotechnical calculations, the designer himself defines the assumed load; therefore the developed calculations and solutions may differ when defining different traffic load. There is an opportunity to use the tandem load defined for bridge design in the calculations by transforming it into a distributed load; however, taking into consideration that the road structure is non-rigid, the distribution of loads in the soil layers differs from load distribution in building structures.

5.1. Traffic load model

In many parts of the world, the tandem load of bridges, according to Eurocode 1: Actions on Structures – Part 2: Traffic Loads on Bridges, is also used for geotechnical calculations. The total load of the tandem is spread over the projection area of the transport. However, taking into account that such load combinations are not expected on the roads, as the maximum permissible axle load is determined by legislation in each country, a vehicle with the maximum permissible load should be used in the calculations.

Considering that the Eurocode describes 4 load combinations, of which the LM3 load is a truck with a semi-trailer that slightly exceeds the permitted axle load (e.g., in Latvia, overloaded log trucks that exceed the legally permitted axle load are often observed), then it is possible to convert LM3 as the calculation load model. Figure 5.1 shows the LM3 load and axis configurations.

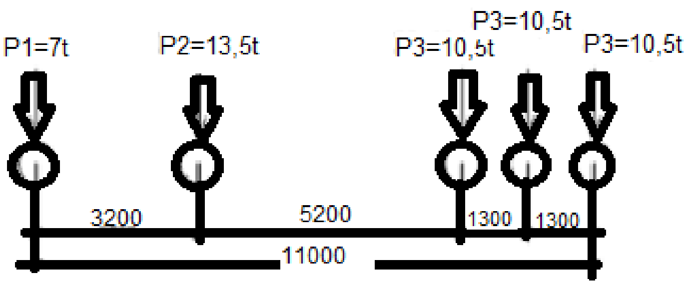

Fig. 5.1. Calculation load model LM3.

In the USA, it is recommended to design geotechnical solutions according to the Geotechnical Design Manual and use traffic loads given in AASHTO Bridge Design Specifications (see Fig. 5.2).

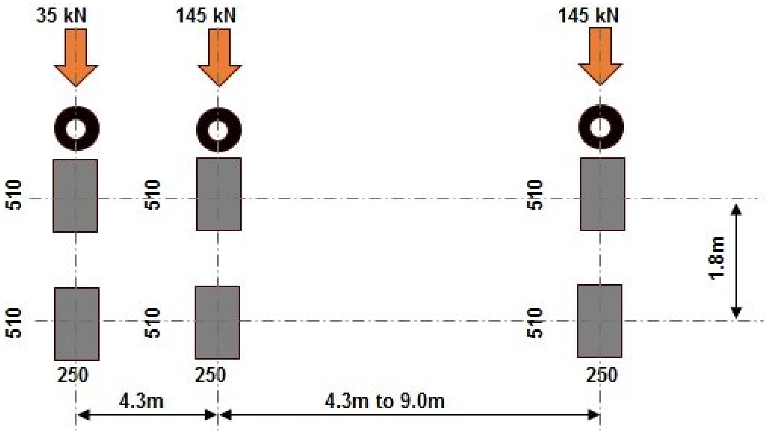

Fig. 5.2. HL-93 design truck AASHTO.

In Germany, before the adoption of EN 1991-2, the traffic load combinations of 33.3/16.7 kPa (first/second lane) on main roads and 16.7/16.7 kPa on secondary roads were used. In both cases they had to be applied on the surface 3 × 6/3 × 6 m.

In Sweden, according to (ATB VÄG 2005), the standard number of axles of heavy vehicles is a crucial parameter for road dimensioning. The standard axle has a load of 100 kN and is supposed to have twin mounted wheels with load evenly distributed, see Fig. 5.3.

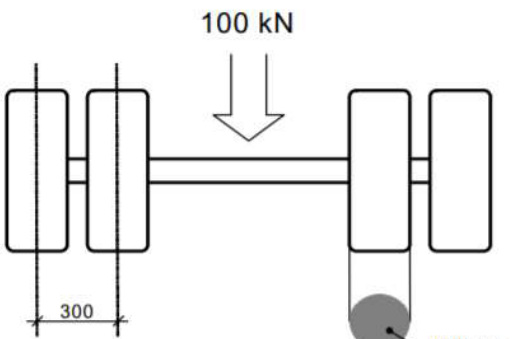

Fig. 5.3. Standard axle used in Sweden.

Considering the fact that different loads are used in calculations, different results are obtained, therefore there is a need to unify the values and application rules for road traffic loads used in geotechnical analyses.

5.2.Calculation model

Three load models are compared in the calculations:

- Distributed Eurocode LM1 load – a tandem system 2 × 300 kN, which is spread over a rectangular surface area, 3 m wide and 5 m long, resulting in a uniformly distributed load of 40 kPa.
- The LM3 load model – a load of 180 kPa applied to an area of 0.4 m × 6 m on each side of the vehicle.
- AASHTO HL-93 load – according to the scheme of the vehicle (Fig. 3), the load is distributed over the contact area of the wheel.

5.3. Analysis of slope stability results

As part of the study, slope stability calculations were performed using various calculation loads defined in the previous chapter.

The developed calculation models and the obtained results are summarized in Table 5.1.

Table 5.1

Calculation Scenarios and Obtained Results

Scenario	Load model	Road construction				Slope	Slip surface location (measured from the face of the slope)	Fs
		Embankment Fs height	Dusty sand	Weak soil	Sandy clay			
1	None	2.0 m	0.9 m	0.5 m	2.0 m	1 : 1.5	0.36 m	1.173
	LM1						4.03 m	0.966
	LM3						2.64 m	0.844
	HL-93						5.66 m	0.521
2	None	1.0 m	0.9 m	0.5 m	2.0 m	1 : 1.5	0.30 m	1,563
	LM1						4.50 m	1,031
	LM3						4.30 m	0.795
	HL-93						5.06 m	0.511
3	None	2.0 m	0.9 m	0.5 m	2.0 m	1 : 2	1.59 m	1.346
	LM1						4.34 m	1.035
	LM3						4.20 m	0.914
	HL-93						5.66 m	0.605
4	None	2.0 m	1.4 m	0 m	2.0 m	1 : 1.5	0.36 m	1.173
	LM1						0.36 m	1.173
	LM3						2.53 m	1.123
	HL-93						2.53 m	0.664
5	None	2.0 m	1.4 m	0 m	2.0 m	1 : 2	0.42 m	1.,442
	LM1						0.42 m	1.442
	LM3						2.58 m	1.273
	HL-93						2.55 m	0.726

Considering the results of all scenario calculations, it was determined that it is not possible to use the HL-93 load model for slope stability calculations. After analysing the results, it was concluded that the LM3 load model has a slightly greater impact on the embankment, road structure, and the soil layer of weak bearing capacity. For this reason, it is recommended to use the LM3 load, transformed into a linear load taking into account the wheel contact area, for slope stability calculations.

5.4. Analysis of the results of global stability/deformation calculations

As part of the study, global stability/deformation calculations were performed using a 3-dimensional finite element calculation program and various calculation loads.

The results of the developed calculation models are summarized in Table 5.2.

Table 5.2

Results of Global Stability/Deformation Calculations

Load model	Scenario									
	1		2		3		4		5	
	Max. def. (cm)	Fs	Max. def. (cm)	Fs	Max. def. (cm)	Fs	Max. def. (cm)	Fs	Max. def. (cm)	Fs
None	1.20	1.173	0.58	1.563	0.99	1.346	0.58	1.173	0.50	1.442
LM1	1.50	0.966	2.00	1.031	1.40	1.035	0.72	1.173	0.67	1.442
LM3	2.80	0.844	3.50	0.795	2.40	0.914	1.30	1.123	1.10	1.273
HL-93	2.00	0.521	1.40	0.511	1.60	0.605	1.20	0.664	0.98	0.726

Taking into account the obtained results, as well as the fact that rut deformations are very often observed on roads and the load is transferred to the pavement only in the contact surface area, the LM1 load model does not reflect the real situation and the true nature of the load that occurs during vehicle passing. The above-mentioned facts indicate that the LM1 load model does not provide accurate calculation results because the parameters of this load do not correspond to the load caused by the vehicle, which is usually transferred to the roads by evaluating the wheel trajectory and the width of the tire contact surface.

Evaluating all the results of slope stability and deformation calculations, it is possible to conclude that using the load model LM3 for geotechnical calculations ensures the greatest safety of the road construction. The applied linear loads, taking into account the wheel contact area, accurately reflect the trajectory of the vehicle and the dynamics of deformation development in the road structure. For these reasons, it is recommended to use the LM3 load model for geotechnical calculations, applying it to each driving lane.

6. EVALUATION OF BEARING CAPACITY OF ROAD STRUCTURE USING STATIC PLATE TEST

The static plate loading test is used to assess the deformation properties of the soil, the load-bearing capacity of the existing foundation, and the compaction of structural layers. This test can be performed on all types of dispersed (loose) soils, embankments and rocky soils, but is not normally used on very soft and fine-grained soils. Due to the accuracy of the test results and the fast data processing, it is very often used to estimate the residual load-bearing capacity of the existing road base.

6.1.Development of a static plate test finite element calculation model

Based on the parameter values of soil layers obtained from the interpretations of the probing data, static plate test simulations using the finite element method were developed as part of the Doctoral Thesis, and the obtained bearing capacity results were compared with the values determined during the geotechnical investigation. The aim was to find out whether the bearing capacity of the existing foundation can be accurately determined by finite element calculations – static plate test simulation, based on the physical and mechanical properties of the soil layers determined during the geotechnical investigation.

6.1.1. Existing road subgrade/foundation

The geotechnical investigation is carried out at the initial stages of the road project development; therefore, it is very difficult to define in which sections of the road it would be possible to envisage the construction of a partial pavement structure. Therefore, it is not possible to determine exactly which of the the existing road's structural layers will serve as the subgrade/base for new road construction, for which the remaining bearing capacity must be determined. During the development of the Doctoral Thesis, it was found that the test results of the static plate test are significantly affected by the size of the trial site pit because the remaining asphalt affects the development of deformations in the base layer, thus the bearing capacity of the base is determined inaccurately.

In road projects, assuming the full construction of the road structure, the minimum bearing capacity of the base/subgrade is 45 MPa. However, during road construction, problems often arise and it is impossible to reach this value, therefore additional funding is needed to build solutions to ensure the carrying capacity.

6.1.2. Static plate test

Static plate load test is a field test which is commonly adopted to determine the bearing capacity and settlement of soil under a given condition of loading as well as the quality of the compaction works performed on shallow foundations.

The plate load test is performed based on German standard DIN 18134 (Testing Procedures and Testing Equipment – Plate-loading Test).

6.1.3. Structure of the static plate test simulation model

During the geotechnical investigation, the static plate test is performed, as described in Subsection 6.1.2. The finite element model and the loading/unloading stages were developed according to DIN 18134 with three cycles – loading, unloading, and reloading. The calculation is modelled using the physico-mechanical properties of the soil layers, which were obtained by performing static and dynamic probe interpretations. Using the photos taken during the geotechnical investigation, the field of view of each probe point and the depth of the static plate test position were determined.

The Mohr-Coulomb model is used for the calculations, which is the most common model used for the calculations of geomaterials and soil layers. The specification of this model and its criterion usually include the Coulomb's hypothesis, which postulated a linear relationship between the in-plane shear strength and the stress applied to it. The model includes five parameters, i.e., Jung's modulus, Poisson's ratio, shear resistance, internal friction angle, and dilation angle, see Fig. 6.1.

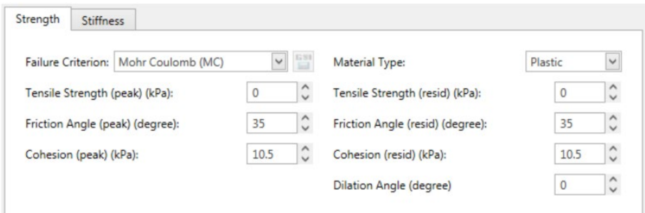

Fig. 6.1. Input window for defining the Mohr-Coulomb model.

When using a finite element program, it is very important to accurately define all output parameters, applied loads, movement restrictions, construction geometry, water level marks, distribution accuracy of finite elements, stages and their parameters, as well as other things. The structure of the finite element program and the approximate geometry of the calculation model can be seen in Fig. 6.2.

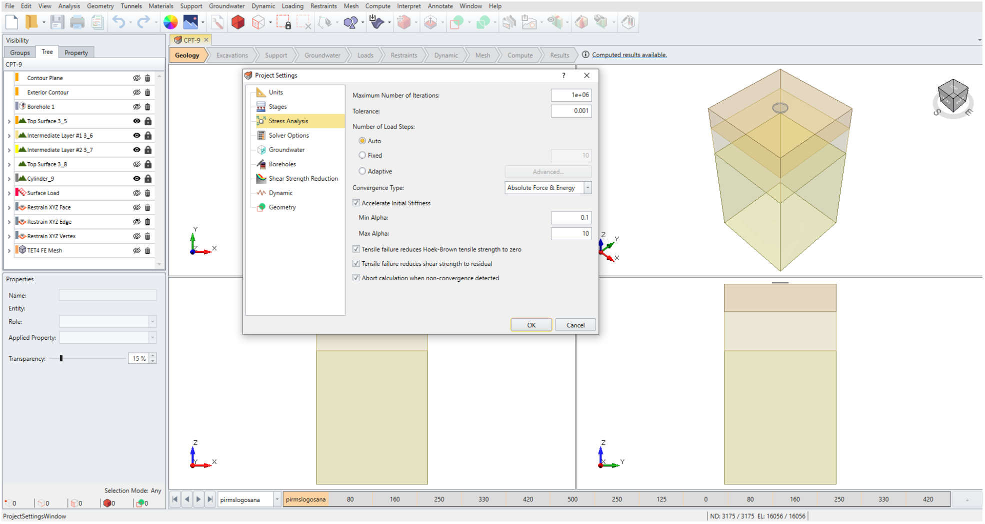

Fig. 6.2. RS3 software interface.

The physico-mechanical properties of the existing soil layers are the most important data that need to be obtained during geotechnical investigation. The following soil/material layer data were defined in the calculation models (see Fig. 6.3): soil unit weight; unit weight of water; type of behaviour (linear, non-linear, etc.); Poisson's ratio of the material; Young's modulus of elasticity; constrained deformation/oedometer module; material type (plastic/flexible); shear resistance of soil layers; angle of soil internal friction; tensile strength of the material; compressive strength of the material; dilation angle of the bottom layers; material condition (drained/undrained); porosity of the soil layer.

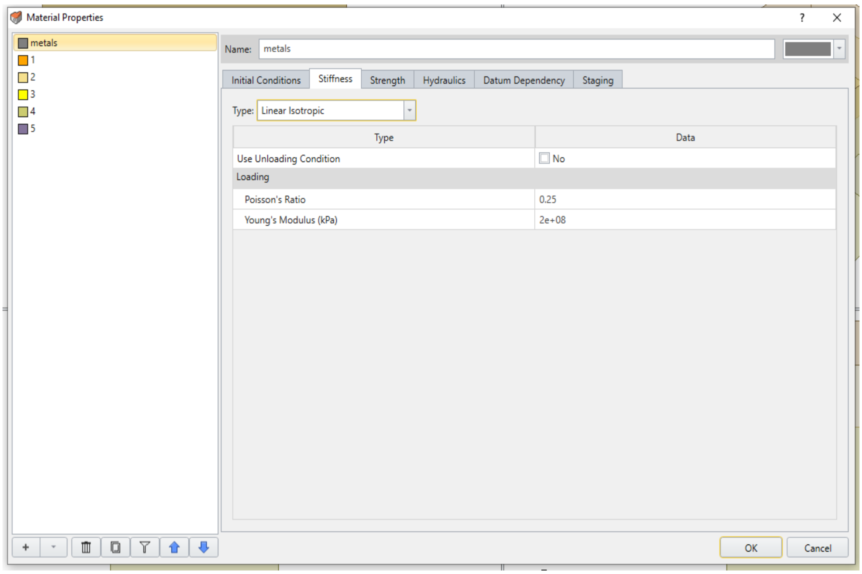

Fig. 6.3. Physico-mechanical property parameters of soil/material layers.

Evaluating all the initial data (thickness of the soil layers, physico-mechanical properties of the layers, loading cycles of the static plate test, and other parameters), a finite element calculation model was developed, see Fig. 6.4.

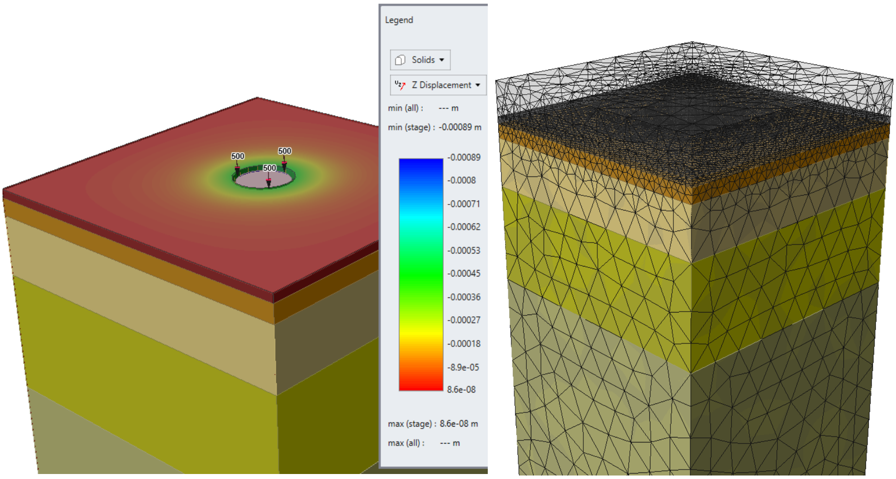

Fig. 6.4. Static plate test simulation model.

In the static plate simulation, the load was applied according to DIN 18134, with 6 loading stages in the first loading cycle, 3 unloading stages, and 5 loading stages in the second loading cycle. At each of the loading stages, the vertical deformation of the static plate was determined and the collected data was processed to obtain a graph of the static plate test (see Fig. 6.5.) from which the bearing capacity values Ev_1 (first loading cycle) and Ev_2 (second loading cycle) of the existing foundation were expressed.

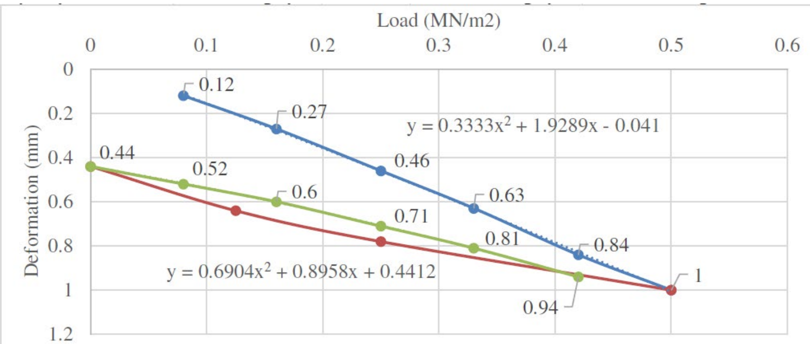

Fig. 6.5. Static plate test simulation results.

6.1.4. Development of analytical calculation formula for Ev_2 calculation

Being aware of the fact that finite element calculations are complicated and calculation software is not available to all engineers and taking into account the high costs of these programs, the development of an analytical calculation formula was carried out in the Doctoral Thesis. It was developed to facilitate the work of designers and to determine the bearing capacity of the existing foundation/subgrade with a simplified approach. In order for the results to be appropriate, the quality and accuracy of the raw data is very important.

The calculation Formula (6.1) was developed based on the physical and mechanical properties of the soil layers, as well as the construction quality control data collected during the road construction works, when the quality of the construction works is checked with the help of the static plate test by determining the bearing capacity of the structural layers. The calculation is made taking into account the constrained deformation modulus M of each soil layer, which can be determined with the oedometer laboratory test or during the geotechnical investigation by performing probing research interpretations. In the direction from the subgrade to the top, the bearing capacity of Ev_2 is calculated above each layer of geological soil. Considering the bearing capacity (Ev_2 value), under each soil layer, the ratio Ev_2/M is calculated, determining the bearing capacity/deformation modulus ratio. Such a ratio needs to be evaluated, because depending on this ratio, the increase in strength/bearing capacity is significantly different.

$$Ev_2 = M_i \cdot X, \tag{6.1}$$

where

$$X = A + (1 - A) - (1 - A) \cdot e^{-B \cdot (H/30)} \tag{6.2}$$

$$B = -0.65 \cdot (1 - A)^2 - 0.75 \cdot (1 - A) + 1.4 \tag{6.3}$$

$$A = Ev_{2i+1} / M_i; \tag{6.4}$$

if $A > 2$, then $B = 2.5$

Ev_2 – bearing capacity of the examined soil/structural layer (MPa);

Ev_{2i+1} – bearing capacity of the soil/structural layer under the examined soil layer (MPa);

M_i – constrained deformation modulus of the soil layer under examined soil/structural layer (MPa);

H – thickness of the examined soil/structural layer (cm).

The developed calculation formula is essentially a graph of the exponential function, and using the thickness and ratio of the soil layer (Ev2/M) it is determined how fast the increase in bearing capacity is expected. Figure 6.6 shows the graph of the determination of the bearing capacity (it is accepted that Ev_{2i+i} is 25 MPa, M is 90 MPa and H – 30 cm). Basically, it is defined that the maximum possible value of Ev_2 can be reached, which corresponds to the value of the constrained modulus – $Ev_2 \leq M$.

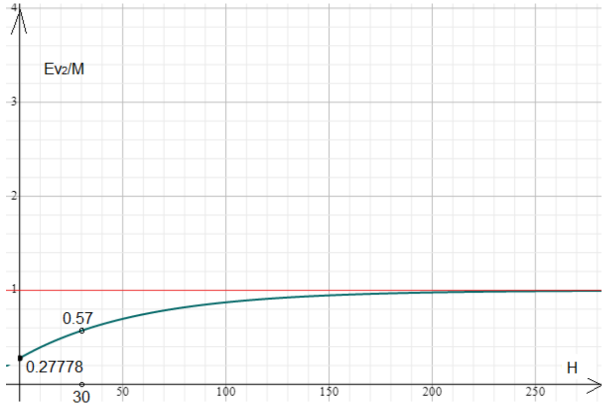

Fig. 6.6. The exponential graph of the described example.

In order to check the accuracy of the developed formula, it was applied in the analysis of geotechnical survey data.

6.2. Evaluation of the residual load-bearing capacity of the existing road structure

6.2.1. Geotechnical research

Justification of geotechnical research – to provide the customer with the necessary information to ensure the development of a full-fledged road pavement reinforcement (reconstruction) project.

6.2.2. Analysis of the base/subgrade bearing capacity of the existing road, A10 *Rīga–Ventspils*

6.2.2.1. Geotechnical investigation of the existing foundation structure

During the geotechnical research, in order to determine the deformation and strength properties of the existing base layer of the road, the static plate loading test was performed at 34 points in the carriageway part.

Using the results of the geotechnical research of the static plate test, a summary of the basic load-bearing capacities of the existing structure has been developed, see Fig. 6.7.

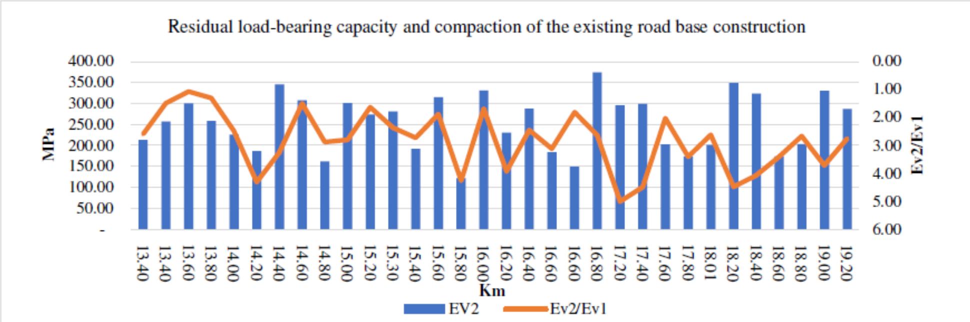

Fig. 6.7. Residual load-bearing capacity and compaction of the existing road base construction.

Figure 6.7 shows the load-bearing capacity and the compaction of the existing base. The analysis of obtained results proved that it is possible to observe the correlation between compaction and load-bearing capacity. As the compaction of the base layer is increasing, its bearing capacity also increases.

Figure 6.8 shows the load-bearing capacity of the existing foundation depending on the thickness of the base layer. There is no unambiguous correlation in the obtained results, and it is possible to conclude that the compaction of the structure has a much more significant effect on the load-bearing capacity of the existing foundation.

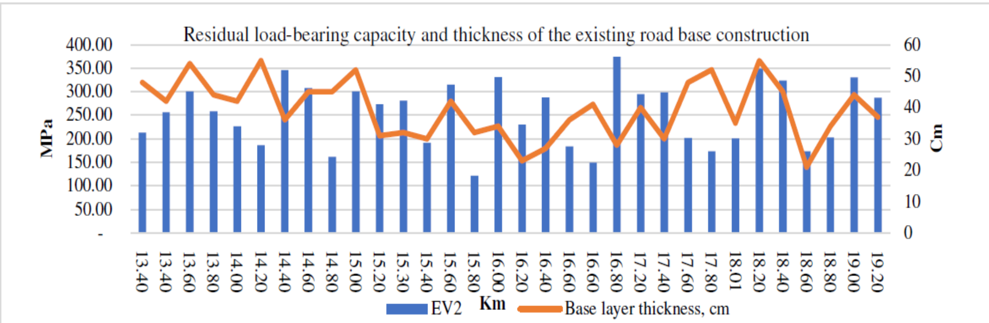

Fig. 6.8. Residual load-bearing capacity and thickness of the existing road base construction.

6.2.2.2. Road reconstruction

In the project the construction of a pavement reinforcement solution was designed consisting of an existing foundation, a 20 cm thick layer of recycled material, and three layers of asphalt. It was defined that it is necessary to achieve a load capacity of 90 MPa of the existing base layer.

The static plate test measurements were made on the existing road base layer during the reconstruction to ensure the possible implementation of the developed solution and the estimated load-bearing capacity of the existing road base. Initially, the old asphalt concrete structure was milled, and the test was performed on the existing foundation under it.

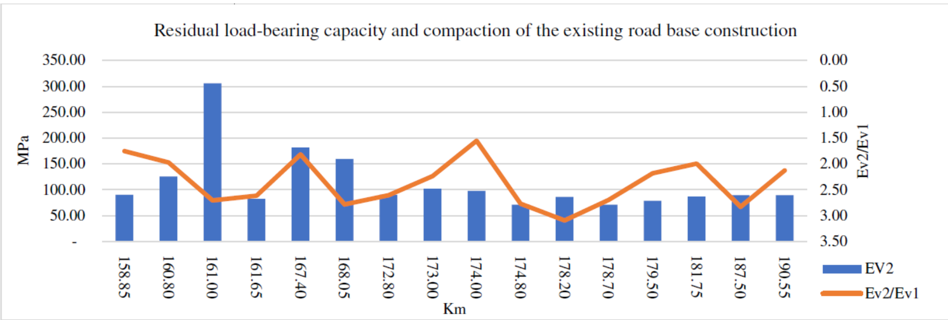

Fig. 6.9. Residual load-bearing capacity and compaction of the existing road base construction.

Figure 6.9 summarizes the load-bearing capacity indicators of the existing foundation determined during the construction. According to the obtained results, it can be seen that the average load-bearing capacity of the existing base is about 90 MPa; therefore it can be concluded that the load-bearing capacity of the existing base has been determined accurately.

6.2.2.3. Residual load-bearing capacity analysis

It is safe to say that the static plate test is performed during the design and construction of each road, so it is important to understand the interrelationships that could be used to determine the load-bearing capacity of an existing foundation. Figure 6.10 compares the load-bearing capacity of the existing foundation found during the geotechnical research and construction.

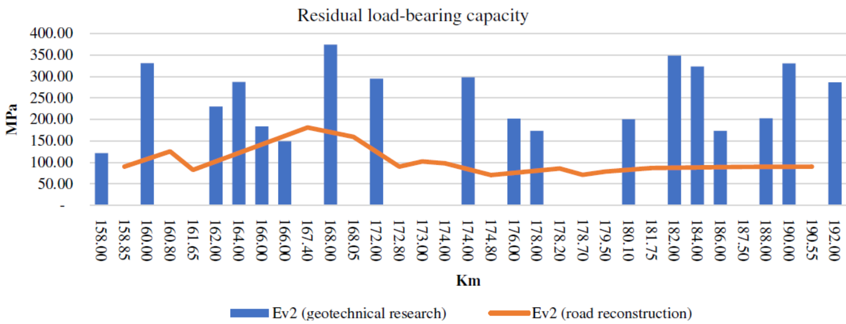

Fig. 6.10. Residual load-bearing capacity.

Comparing the load-bearing capacity determined during the project development and construction, it can be concluded that the results obtained in the geotechnical research are about 1.8 times, or by 80 % higher than those determined during the construction.

One of the most important factors influencing the results could be the different static plate test loading conditions. During the geotechnical research, a small area of asphalt concrete is cut out to form a trial site pit in order to be able to get to the existing foundation structure, perform a static plate test, and determine which soil layers are in the road structure and ground. During the construction, the static plate test is performed when there is no other material on top of the tested layer that could affect the static plate test results. In order to ascertain how much the load-bearing capacity values of the existing base change under different test conditions, a theoretical finite element calculation was performed by simulating a static plate test.

According to the finite element calculation model, it was determined that the applied load spreads within a radius of approximately 1.5 m from the loading centre. If the old asphalt concrete is above the existing base layer structure, the soil layer deformations during the static plate test are slightly smaller (maximum deformation without asphalt layer – 2.8 mm, but with asphalt layer – 2.3 mm). It is because the base layer cannot deform sideways and up, as the asphalt layer does not allow it.

Significant differences in the results were obtained in the calculated theoretical load-bearing capacity of the existing base:

- construction without asphalt concrete surface (road construction) – $Ev_1 = 105.97$ MPa; $Ev_2 = 152.58$ MPa; $Ev_2/Ev_1 = 1.43$;
- construction with asphalt concrete surface (geotechnical research) – $Ev_1 = 117.26$ MPa; $Ev_2 = 203.39$ MPa; $Ev_2/Ev_1 = 1.73$;
- construction with circular trial test pit – $Ev_1 = 103.91$ MPa; $Ev_2 = 333.70$ MPa; $Ev_2/Ev_1 = 3.21$.

All three developed finite element calculation models are based on the same theoretical material properties, but each model has different loading conditions. After analysing the data, we can conclude that the greatest influence on the test results of the static plate test is provided by the loading conditions, or the fact whether another layer is built above the test layer, which could affect the accuracy of the results.

6.2.3. Data analysis of geotechnical research of road P86

In order to determine which of the geotechnical research methods (the static probe or the dynamic probe) provides more appropriate soil parameters, static plate test simulations for road P86 were performed using the data interpretations of both probing methods.

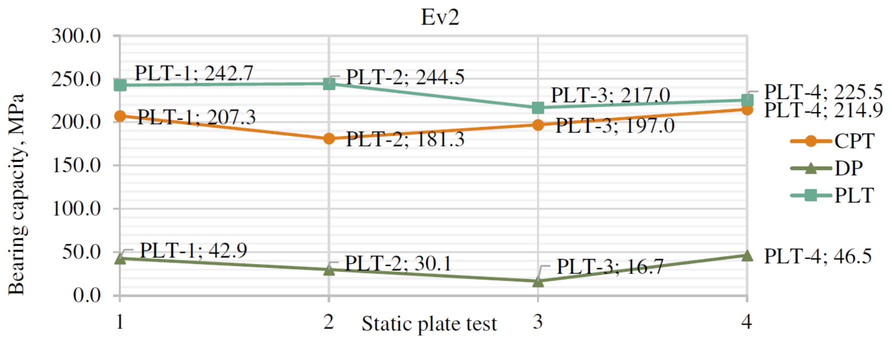

Fig. 6.11. Residual load-bearing capacity of the existing base of the first loading cycle.

Fgure 6.11 shows the bearing capacity of the existing base. Finite element simulation using the static probing test (CPT) data provides relatively accurate results compared to the static plate test (PLT) performed during the geotechnical investigation. The calculation using the dynamic probing data (DPT) interpretations gives a much lower bearing capacity of the existing foundation, so it is not possible to use these data for static plate test simulation.

During the geotechnical investigation, the static plate test on the roadway section is mostly performed in the trial test pit. It is created by removing the existing asphalt layers approximately the size of the diameter of the static plate, so the remaining asphalt concrete layers have an impact on the course of the test and the obtained results. The analytical calculation formula developed as part of the Doctoral Thesis cannot evaluate the asphalt layers left next to the static plate test, therefore it is not possible to directly compare the data of the static plate test performed during the geotechnical investigation with the results of the analytical Ev_2 calculations.

In order to make a comparison and to make sure that the developed formula (Eq. (6.1)) gives appropriate results, a simulation of the static plate test was carried out by removing asphalt layers in the entire roadway area. Calculation results and comparison are shown in Fig. 6.12. Analytical calculation results were obtained using Formula (6.1) and based on interpretations of static probe data.

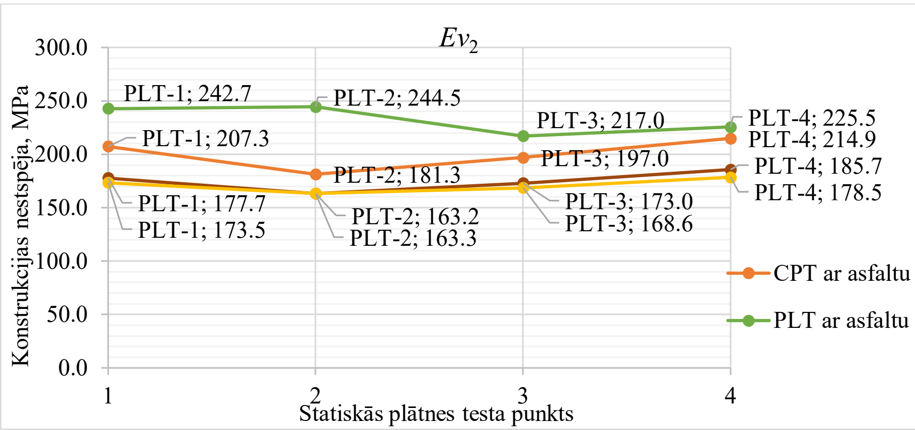

Fig. 6.12. Residual bearing capacity of the existing structural foundation of the P86 road.

Based on the results of the calculation, it is possible to conclude how much influence the asphalt next to the trial test pit has on the bearing capacity of the existing foundation. The difference in the simulation results of the finite element static plate, comparing the calculation with and without the existing asphalt, is 30 MPa. Thus, we can conclude that the asphalt layers adjacent to the slope and its thickness can significantly influence the results of the static plate test performed during the geotechnical investigation.

The results of analytical calculation and finite element static plate simulation without asphalt structure are very similar, and the differences are minimal.

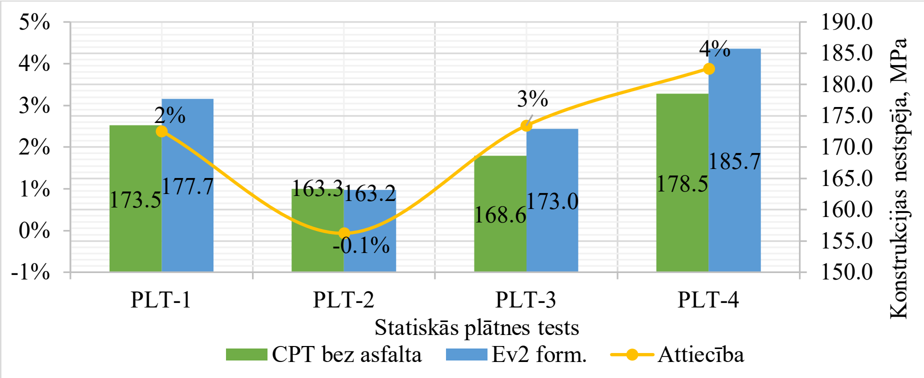

Fig. 6.13. Comparison of the obtained results.

The largest difference in results was 4 percent, while the smallest difference was within 0.1 percent. The values of the bearing capacity of the existing foundation determined by both methods are equivalent. We can conclude that the developed calculation formula provides objective results of the bearing capacity of the existing foundation, and Formula (6.1) can be applied for the assessment of the existing foundation using CPT data interpretations.

6.2.4. Data analysis of geotechnical research of the road A10 13.30– 19.20 km section

As part of the Thesis, the data of geotechnical research and construction work quality of the road A10 (*Riga–Ventspils*) were analysed. During the road construction, a test section was made, where 5 static plate tests (PLT) and 5 static probing tests (CPT) were duplicated on unbound pavement structures.

The results of the calculations done with the finite element method were compared with the results of the static plate test, which was carried out on the road section.

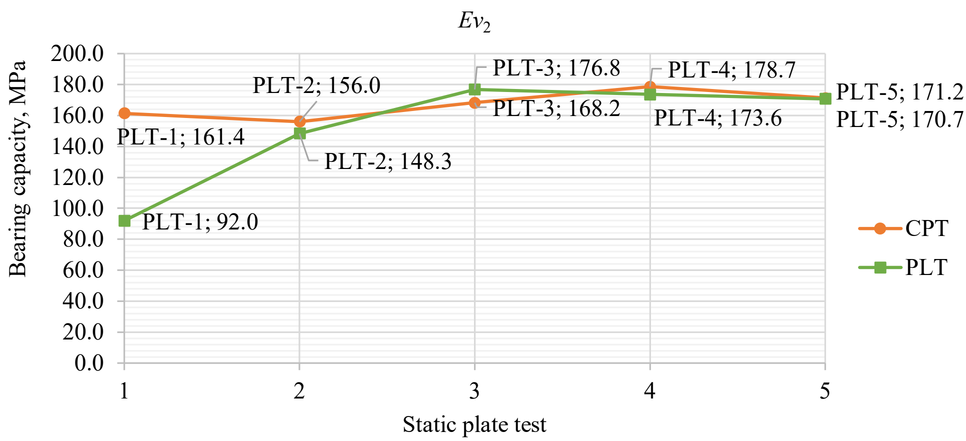

Fig. 6.14. Residual load-bearing capacity of the existing foundation.

Figure 6.14 shows the bearing capacity of the constructed base layer. The results obtained are very accurate. It can be concluded that the residual bearing capacity of the existing foundation can be determined by the finite element method by simulating the static plate test using the physico-mechanical properties of the soil obtained from the interpretations of the static probing test.

The bearing capacity of the foundation determined during the geotechnical research at the 1st point is relatively much lower than in other 4 points. Therefore, the static plate loading test performed on site may have been incomplete, and the obtained data have been inaccurate.

An analytical calculation formula was developed as part of the Doctoral Thesis, and a comparison of CPT, PLT, and analytical calculation was made to ensure that the developed Formula (6.1) provides appropriate results. The calculation results and comparison are shown in Fig. 6.15.

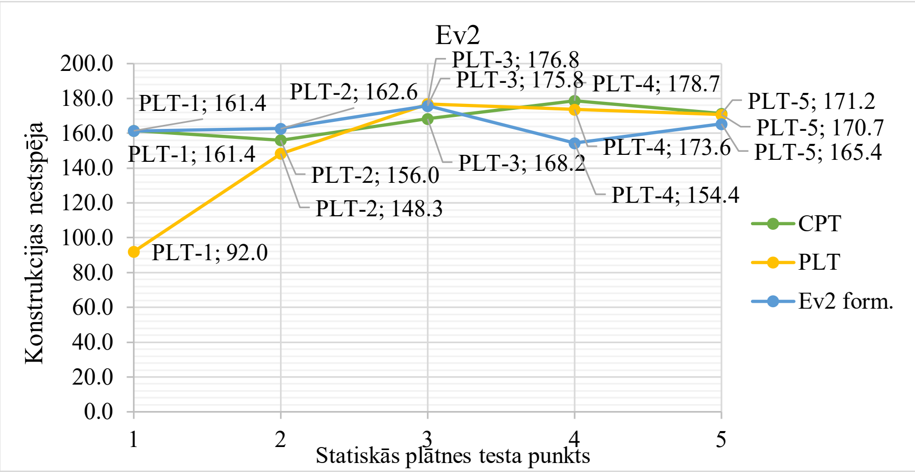

Fig. 6.15. Residual bearing capacity of the existing structural foundation of the A10 road.

The bearing capacity of the existing foundation can be evaluated by performing the static plate test simulations using static probe data interpretations.

With the developed analytical calculation formula, it is possible to objectively determine the bearing capacity of the existing foundation. If during the geotechnical investigation a static probe was conducted, then its data interpretations can be used in the analytical determination of the bearing capacity of the existing foundation.

It is not possible to use the dynamic probe interpretations for the simulation of the static plate test because the obtained results show a significantly lower bearing capacity.

The developed static plate test simulation method for modelling the bearing capacity of the road structure provides very accurate results when the calculations are performed on flexible pavement layers without creating a trial test pit, but fully removing the asphalt layers.

7. CONCLUSIONS

The aim and the tasks set in the Thesis have been achieved. A calculation method has been developed for modelling the bearing capacity of road structures using the characteristics of soil layers and other materials and a transport load model has been developed that reflects the real impact of traffic load on the road structure and can be used for geotechnical calculations and the development of project solutions.

Based on the results of the Doctoral Thesis, the following conclusions were drawn:

1. For the first time in Latvia, a comparison was made of the values of soil parameters interpreted by different probing methods. Geotechnical investigation methods were mostly chosen taking into account the cost of investigation. It is very important to determine the quality of the obtained geotechnical investigation data because they can significantly affect the service life of the structure.
2. As a result of the research, it has been determined that the interpretations of the static probing show the highest values of the parameters of the soil layers. It showed a higher value of the constrained deformation modulus, an average of 10 times higher strength than DCP, and a 2 times higher strength than the interpreted values of DMT. The choice of the geotechnical investigation method can significantly affect the project solutions and construction costs and create a situation where the developed project solutions cannot ensure the serviceability of the road.
3. According to the calculations, it was determined that 60–90 % of the settlement of the total structure develops in the soil layer of weak bearing capacity, therefore the parameters of the soil layer of weak bearing capacity have the greatest impact on the calculation results. Comparing the results of the peat layer consolidation laboratory test with the CPT and DMT interpretations, it was concluded that the dilatometer study determined the value of the soil deformation modulus very accurately – the difference was less than 2 MPa, but the values determined by the static probe were too high – approximately 12 MPa higher. Therefore, it was concluded that the calculations using the static probe data can provide overly optimistic final results.
4. The obtained road construction deformation calculations showed significant differences in results. The largest difference was determined by comparing the calculations using the CPT and DCP interpretations, which was 25 cm, or 600 %. The structural consolidation/settlement calculations using the static probe data showed an average of 3 times smaller deformations as determined by the dilatometer investigation and 6 times smaller than determined by the dynamic probe. In addition to the probing studies, it is necessary to conduct the laboratory tests of undisturbed samples. Thus, it would be possible to check whether the developed solutions are based on conservative, adequate or atypically high physical and mechanical properties of the soil layers, and it would be possible to verify the obtained results of interpretations and, if necessary, perform data correction.
5. The obtained results demonstrate that the dynamic probing method showed the lowest values of soil parameter interpretations and higher consolidation deformations and biggest

slope stability problems. The geotechnical solutions developed based on the DCP interpretations provide 60 % more structural safety compared to the CPT and DMT, but thus increase the construction costs.

6. The study determined that the tandem load LM1 defined for bridge design is often used in road geotechnical calculations, spread over a 3 m × 5 m rectangular area. Taking into account that on roads, rut deformations that develop under the wheel trajectory are most often observed, therefore the LM1 load does not accurately reflect the effect of traffic load, because in this model the entire amount of load is also distributed over the area between the wheels and the deformations develop evenly.
7. The use of the developed transport load model LM3 in geotechnical calculations increases the safety of road construction by 20 %, and the applied linear loads accurately reflect the trajectory of the vehicle and the dynamics of deformation development in the road structure. According to the results of the study, it was determined that the LM3 load model can be used globally in other countries as well, taking into account the maximum axle load determined by the legislation of each country, and thus modifying the size of the load but maintaining its application scheme.
8. Within the scope of the study, it was determined that the greatest influence on the results of the static plate test is due to the different testing conditions. The existing asphalt concrete or other type of construction above the layer to be tested prevents obtaining adequate results because the created area is too small and the base layer cannot deform by pushing out to the side and up. According to the performed analysis, it was determined that the existing asphalt concrete layer influences the results of the static plate test performed during the geotechnical investigation in an average amount of 40 %, compared to the results obtained during the construction. Therefore, during the author's supervision, it may be necessary to make corrections to the project.
9. The innovative static plate test finite element calculation model developed as part of the Doctoral Thesis provides very accurate results when performing calculations on unbound pavement layers without the creation of a trial test pit (without adjacent embankment affecting the test results). The obtained results demonstrate that the static plate test simulation using the static probing interpretations shows a very accurate bearing capacity of the existing foundation. The difference between the results of the on-site plate test and the test simulated with the finite element program is 3 %. Therefore, it is determined that the developed calculation model can be used to determine the bearing capacity of the existing foundation at any desired depth.
10. As part of the study, it was determined that the difference between the results of the static plate test performed on site and the results determined by the analytical calculation formula is 5%. The developed analytical calculation formula for evaluating the bearing capacity of the road structure provides objective results, and Formula (6.1) can be applied to determine the bearing capacity of the existing foundation using the CPT data interpretations.

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Since 2014, he has been a leading road construction engineer at JSC "Ceļuprojekts" and, since 2021, a scientific assistant at Riga Technical University. His scientific interests are related to the development of safe, high-quality pavement construction and project solutions and analysis of the geotechnical situation.