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Using Resilient Modulus to Determine the Subgrade Suitability for Forest Road Construction

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Received: 20 October 2020; Accepted: 14 November 2020; Published: 16 November 2020

Abstract: Forest roads are often constructed in environments with low bearing capacity of the subgrade. The subgrade then has an effect on their service life and damage. According to the methodology of the American Association of State Higway and Transportation Officiales AASHTO, the design of pavement is divided into three levels according to the intensity of the traffic load. For pavements with the highest load intensity, preparing the resilient modulus from a cyclic triaxial test is required. For other traffic load classes, including forest roads, the methodology allows the use of the estimate of resilient modulus value determined from other tests. In the laboratory at the Faculty of Forestry, Mendel University of Brno, the method from the Delft University 2009 was tested and subsequently modified, using a standard CBR machine for repeated loading. A total of 276 samples from various types of forest road subgrade from the Czech Republic were tested by the method of repeated loading on the CBR machine, from which the values of the Resilient Modulus were newly labelled $M_{r,CBR}$. The results of the statistical analysis showed a large variability of $M_{r,CBR}$ values and wide intervals of its occurrence for individual types of subgrade. The variability was subjected to analysis and the influence of basic geotechnical parameters on the values of $M_{r,CBR}$ was analyzed. A fundamental correlation was found between the value of $M_{r,CBR}$ and the value of the plunger stress, which reached values exceeding the bearing capacity of the soil types using the Delft University method. It is necessary to limit the plunger stress during cyclic loading up to the failure limit or even better to the expected traffic load. The modified procedure results show a more consistent behavior of the modulus.

Keywords: low volume road; pavement; soil; resilient modulus; CBR cyclic test

1. Introduction

Forest roads, which are ranked among low volume roads by the American Association of State Highway and Transportation Officials AASHTO based on the transport intensity [1], are an integral part of the road transport system. They are used to ensure access to the areas that need to be accessible for economic, social, recreational, and security reasons. These roads often need to meet criteria that are in conflict with each other. Compared to other roads, forest roads are less transport-intensive; however, the natural conditions require specific attention when designing pavement layers. The roads often lead through a terrain where the subgrade has an unfavorable water regime, low load bearing capacity, and high longitudinal slopes, which leads to faster degradation of the pavement [2]. Although forest roads in the Czech Republic are in the lowest road category with the smallest demands on the quality of input characteristics, they have to simultaneously meet the requirements regarding load bearing capacity according to TP 170 (2011) and design methodology for low volume roads (LVRs) [3].

Only natural materials are preferred and mostly used both for the subgrade improvement as well as for the pavement layers. These roads often lead through valuable natural areas and thus become a part of unique ecosystems; it is therefore necessary to approach their design with respect to the protection of the adjacent ecosystems [4].

Forest roads in the Czech Republic are designed in compliance with the valid national regulations and standards applicable to all categories of roads—technical conditions [5], forest road network [6], and LVRs methodology [3]. Not only in the Czech Republic, the methodology for road design of all categories is based on empirical experience [7] and the knowledge of California Bearing Ratio (% CBR) of the subgrade [8].

The most important non-European regulation for road design is the American Association of State Highway and Transportation Officials (AASHTO) methodology. The AASHTO has long been involved in the road design procedures and it publishes guides for both design procedures as well as laboratory procedures to determine the necessary material characteristics. The original Guide for Design of Pavement Structures (GDPS) was updated to the Mechanistic-Empirical Pavement Design Guide [9] in 2004, and the original empirical design method was extended to a mechanistic-empirical method. The guide divides road design into three levels based on the average daily intensities of heavy vehicles in the design period and defines how to determine the resilient modulus (M_r) of the subgrade for the design pavement layers. For the first design level, where high transport loads are expected, the modulus M_r, of the subgrade is determined by the triaxial cyclic test [10]. For the second and third design levels where the daily intensity is a maximum of 400 heavy vehicles, this test is not recommended for its complexity and it is possible to replace M_r with the so-called design modulus E_D, determined from other soil characteristics, e.g., the CBR [7]. However, this pavement layers design based on the subgrade CBR has gradually become insufficient even for the second and third design levels, because it does not describe the real deformation behavior of the material, does not allow using new materials, assessing the layer thickness, and using numerical analyses and thus minimizing the consumption of natural nonrenewable resources [11,12]. Last but not least, this design method does not allow including climatic conditions in the design [13]. Additionally, the use of conversions between the CBR and the design modulus E_D, brings a number of inaccuracies to the road design [14]. Therefore, the present MEPDG methodology recommends replacing these conversions by the resilient modulus M_r, or at least by its estimation based on the laboratory cyclic tests.

Reflecting this global trend in road design and sustainable development with the protection of nonrenewable resources, a project of the Czech Technology Agency TA 01020326, 2011–2014 was implemented, dealing with the road design optimization not only for forest roads, but for LVRs in general. The one project aim was to find the suitable laboratory method to determine the resilient modulus estimate that would meet the cyclic loading criteria, would be time and financially affordable, and will substitute the expensive triaxial test.

Therefore, the procedure designed by the Delft University [15] to estimate the effective resilient modulus $M_{r,eff}$, was used, employing the standard CBR test equipment for cyclic loading. This method of estimating the resilient modulus was tested and innovated in the laboratories of Mendel University in Brno (MENDELU) and the geotechnical laboratory GEOSTAR s.r.o. Within the project, software P 304642 has been developed for the automated test implementation, which was patented in 2014 [16]. It controls the cyclic loading procedure and determines the parameters for the resilient modulus calculation, which is labelled $M_{r,CBR}$.

The performed numerical simulations [17] show that the behavior of roads is mainly affected by the subgrade load bearing capacity. In the numerical analyses performed, based on finite element (FE) models, the subgrade resilient modulus has a dominant influence on the resulting behavior and thus on the quality of the road structure as a whole [18]. Therefore, an extensive experimental study of subgrade soils was proposed to monitor their behavior during cyclic testing on the CBR device. The aims were to determine the intervals of the resilient modulus for the main subgrade soil types, to improve the design by using the modulus obtained from the cyclic test while respecting AASHTO recommendations, and thus facilitate the preparation of the adequate input characteristic respecting the real transport loading [19] and simulating the future state of the composition material as realistically as possible.

The present paper summarizes the results of long-term research of the deformation behavior of subgrade soils in the Czech Republic and the analysis of the resilient modulus $M_{r,CBR}$ obtained from cyclic testing. The determination of the modulus was based on the Dutch theory of the effective resilient modulus for unbound materials [15]. The statistical analysis of the obtained results for the basic subgrade soil types according to the Unified Soil Classification System [20] is presented.

2. Materials and Methods

2.1. Study Area, Samples, and Geotechnical Analysis

The subgrade deformation behavior was measured using materials from the subgrade active zone sampled from forest roads tested between 2011 and 2014 during the implementation of project TA 01020326. The road selection included a wide range of subgrade soils according to USCS classifications [20,21]. The forest roads from different regions of the Czech Republic were included. The methodology of sampling was based on the failure rate of forest roads and samples were taken in places with supposed low bearing capacity of the subgrade. There were roads built in various geological environments of the Czech Republic, consisting of:

- eluvial rocks:
    - metamorphic rocks—gneiss from the Bohemian-Moravian Highlands—siSa, grsiSa, siGr;
    - igneous rocks—granites from the Bohemian-Moravian Highlands—csaCl, sagrSi, siSa, clGr;
    - diagenetic lithificated sediments of sandstone, greywacke from the Nízký Jeseník Mts.—Cl, siCl, csaCl, sagrSi, grsaCl;
    - Devonian limestone from the Moravian Karst—csaCl,sagrSi, clSa, siSa, siGr;
    - Paleogenic diagenetic lithificated sediments of the flysch belt from the Beskydy Mts.—Cl, grsaCl;
- sediments:
    - cretaceous clays and sands from the Drahanská Highland—Cl, siCl, saclSi;
    - Neogenic and Quarternary clays of the Lower Morava Valley—saciSi, csaCl, grsaCl.

Materials from the subgrade of 11 forest roads in total were analyzed. The samples for determining the resilient modulus were taken from the active zone of the forest roads, i.e., from a depth of 500 mm below the road carriageway.

A total of 48 samplings of the subgrade material were performed to achieve a representative quantity of $M_{r,CBR}$ values. Six samples were produced from each sampling. The samples were compacted into test mold for the CBR test with a diameter of 152 mm and a height of 117 mm using the Proctor Standard energy and they were conditioned to the optimum humidity and maximum dry density according to [22]. The samples thus prepared were subjected to the appropriate cyclic test for the determination of $M_{r,CBR}$ value and a set of six values was statistically evaluated. In total, 276 samples for nine soil types were tested. After the cyclic test, the maximum dry density and the humidity of each sample were measured and their average values for each class were determined.

Geotechnical tests necessary for the classification according to the relevant European standards were carried out for each sampling. The geotechnical analyses consisted of humidity test according to standard [23], sieving and aerometry test according to standard [24], and consistency (plastic-liquid limit) or Atterberg boundary test according to standard [25]. The tests serve for the basic soil classification based on their granulometric composition and Atterberg plastic-liquid limits for the classification of soils according to the Unified Soil Classification System (USCS).

2.2. Laboratory Analysis—Cyclic CBR Tests

To prepare the resilient modulus, the Dutch procedure was selected to estimate the effective resilient modulus from the cyclic CBR test of base and sub-base granular materials, based on the repeated standard CBR test to a constant penetration depth of 2.54 mm [15]. The principle of this cyclic test is the application of repeated loading on a sample from the road subgrade simulating the effect of transport. The loading was carried out using a device for the CBR determination in compliance with valid standards for sample preparation [22] and for the implementation of the CBR standard test [8], i.e., penetration at a standard speed of 1.27 mm/min by a plunger with a diameter of 50 mm. In the cyclic test the sample was loaded to a penetration depth of 2.54 mm, then unloaded until the load dropped to zero, and reloaded until the required penetration was achieved. This process was repeated until the elastic deformation value w, reached a constant value, i.e., $w_i - w_{(i-1)} = 0$ (condition A), where i is the cycle number. This was achieved in approximately 50 cycles. To calculate the resilient modulus $M_{r,eff}$, deformation w and stress σ from the last test cycle of the selected sample was used according to condition A and Equation (1):

$$M_{r,eff} = \frac{C_1\left(1 - \mu^{C2}\right)\sigma_0 a}{w^{C3}} \tag{1}$$

where:

$M_{r,eff}$ = resilient modulus estimate of the material tested (MPa),
w = elastic deformation (mm) by condition A,
a = radius of the circular plunger (mm),
σ_0 = stress under the plunger (kPa),
μ = Poisson's ratio of material,
C_1 = mean 1.797 for full slip = 1.375 for full friction,
C_2 = mean 0.889 for full slip = 1.286 for full friction,
C_3 = mean 1.098 for full slip = 1.086 for full friction.

This procedure has been innovated, modified, and validated at MENDELU to be applied to various soil types of the subgrade. In contrast to the Dutch procedure, the standard mold dimension was used for the CBR standard test as it is suitable not only for soil, but also for tests of gravel-like material of Gr type according to USCS. For the actual cyclic test, the adverse nature of the subgrade soils, their cohesion, greater elasticity, and low load bearing capacity were considered, which often led to an increase in the duration of the tests, up to 200 cycles. Therefore, the condition for the loading termination was modified to: until t the differences of the three last consecutive deformations are 0.005 mm (condition B) at most. To calculate the resilient modulus $M_{r,CBR}$, the effect of friction was modified using the mean values of constants C_1, C_2, C_3 [14]. To calculate the modulus deformation value w′ and stress σ from the last test cycle were used according to condition B and Equation (2)

$$M_{r,CBR} = \frac{C'_1\left(1 - \mu^{C'_2}\right)\sigma_0 a}{w'^{C'_3}} \tag{2}$$

where:

$M_{r,CBR}$ = resilient modulus estimate of the material tested (MPa),
w′ = elastic deformation (mm) by condition B,
a = radius of the circular plunger (mm),
σ_0 = stress under the plunger (kPa),
μ = Poisson's ratio of the material tested,
C'_1= 1.5865 for the mean friction,
C'_2= 1.0875 for the mean friction,
C'_3= 1.0920 for the mean friction.

Furthermore, the permissible penetration depth that affects the plunger stress values was subjected to a detailed analysis. When applying the load to a constant penetration depth of 2.54 mm, according to the CBR standard test, high stress values are observed in the plunger, exceeding the maximum load bearing capacity of the material for many soil types. Soil is a natural, heterogeneous and discontinuous environment, the deformation behavior, strength as well as variability of mechanical properties depend on many factors—e.g., the genesis, soil type, lay-off of unbound materials, compaction rate [26,27] given by the Proctor Standard energy, the liquid phase amount [12], the number of repeated loading cycles as well as on maximum load bearing capacity. The resilient modulus must reflect these factors [28] and be obtained from an adequate laboratory test, in which the future loading by repeated passages of transport vehicles is realistically simulated with the future stress interval in the structure. At the same time, the test must not violate the sample and exceed the maximum load bearing capacity of the material [29,30]. After the implementation of this study, the depth of the maximum penetration was adjusted with respect to the expected maximum possible stress and the test was prepared with a defined value of plunger stress [31].

The cyclic CBR procedure from 2009 tested on unbound base and sub-base materials [32] assumed that this procedure yields relatively accurate deformation characteristics of the materials tested to obtain the resilient modulus estimate, at the same time allowing samples to be prepared at different humidity and changing compaction rates, and is in fact an overall expression of the material stiffness in the form of CBR. It is not a characteristic of the material, but a characteristic of the sample. As observed in studies on cyclic triaxial [33], resilient modulus, M_r, is not a constant property of materials, but depends on many factors and, depending on the material tested, it is most affected by the maximum dry density, water content, and the load size given by the applied stress. Therefore, given their variability, it cannot be assumed that one value of modulus M_r can be assigned to one soil type, as there are an infinite number of values depending on the test conditions.

The aims of this work were therefore to innovate the Dutch procedure of estimating the resilient modulus from cyclic CBR by analyzing subgrade materials in detail, to monitor the levels of plunger stress and thus verify its suitability for subgrade soils. Due to the variability of deformation characteristics depending on the possible variability of humidity and the maximum dry density of the samples [33], the effort was to provide occurrence estimates—an appropriate range of variations—of the resilient modulus, $M_{r,CBR}$, for basic soil type with a uniform preparation of samples at optimum humidity, determined by the Proctor Standard test. The minimized influence of different water content values was assumed to reduce the variability of $M_{r,CBR}$ due to different conditions of the sample and to allow monitoring the effect of granulometry—from different locations of the Czech Republic—for one soil type by USCS, thus providing representative occurrence intervals of the resilient modulus for efficient LVRs designs.

2.3. Statistical Analysis

The following values were calculated for each data set: mean, standard deviation, coefficient of variation, minimum and maximum values, and 0.05 and 0.95 quantiles. The mean indicates what value of $M_{r,CBR}$ can be expected; the standard deviation and the coefficient of variation indicate the expected dispersion of values from the mean; the minimum and maximum values show the estimated interval where the values can be expected. The 0.05 quantile is a value of $M_{r,CBR}$ for which we can expect with a 5% probability that the values will be smaller, or with a 95% probability that they will be greater than the 0.05 quantile. The 0.95 quantile case is analogical. In addition, the difference between the two quantiles determines the interval where the values will occur with a 90% probability.

Each sampling and each soil type were statistically evaluated based on the relevant classification. The extent of the samplings and thus the number of samples analyzed was different within each soil type, depending on the number of samplings taken from the soil type after their geotechnical classification.

3. Results

The geotechnical tests were carried out on 276 samples from 46 samplings. Once the geotechnical tests were finished, the different soil types were classified according to USCS. The analyzed samplings were classified in a total of nine soil types according to USCS. The marking of localities, the classification, and the mean values of the maximum dry density and humidity are presented in Table 1.

Table 1. Soil classification.

Locality Number N°	Soil Type USCS	Sampling Number	Sample Number	Mean Density $kg{\cdot}m^{-3}$	Mean Humidity %
1	Cl	10	60	1598.8	23.8
2	siCl	3	18	1655.9	20.7
3	saclSi	2	12	1748.3	18.6
4	csaCl	5	30	1813.7	15.7
5	sagrSi	6	36	1858.5	13.4
6	grsaCl	4	24	1635.5	21.5
7	siSa	10	60	1796.0	14.7
8	grsiSa	2	12	1827.3	13.6
9	siGr	4	24	1929.6	12.7

3.1. Statistical Results $M_{r,CBR}$ from the Cycle Test

The results of statistical analysis are for individual soil types are presented in Figures 1–9. For each sampling, the $M_{r,CBR}$ mean, and 0.05 and 0.95 quantiles are listed. These statistical quantities are also given for the whole soil type.

- Soil N°1—Cl

The Cl soil type contains a total of 10 samplings, see Figure 1. The obtained $M_{r,CBR}$ mean of the whole soil type (obtained from the statistical evaluation of all 60 samples) is 123.35 MPa. The coefficient of variation of the whole soil type is 0.83. The minimum value is 36.9 MPa, the maximum value is 429.9 MPa. The 0.05 quantile is 39.0 MPa, the 0.95 quantile is 371.7 MPa for the entire soil type. The results show two distinct subgroups of the values of $M_{r,CBR}$. In the first subgroup, the values of $M_{r,CBR}$ reach to about 150 MPa; in the second up to a value of about 420 MPa.

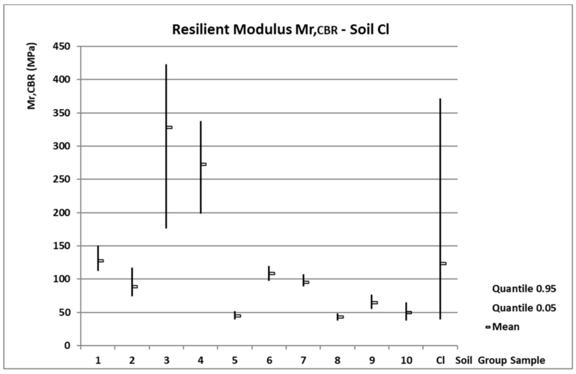

Figure 1. Statistical quantities—mean, 0.05 quantile, 0.95 quantile of $M_{r,CBR}$ for Cl soil.

- Soil N°2—siCl

The siCl soil type contains a total of three samplings, see Figure 2. The obtained $M_{r,CBR}$ mean of the entire soil type (obtained from the statistical evaluation of all 18 samples) is 140.8 MPa. The coefficient of variation of the entire soil type is 1.08. The minimum value is 14.9 MPa, the maximum value is 375.9 MPa. The 0.05 quantile is 18.7 MPa, the 0.95 quantile is 299.4 MPa for the entire soil type.

The results show two distinct subgroups of the values of $M_{r,CBR}$. In the first subgroup, the values of $M_{r,CBR}$ reach to about 30 MPa; in the second, up to a value of about 380 MPa.

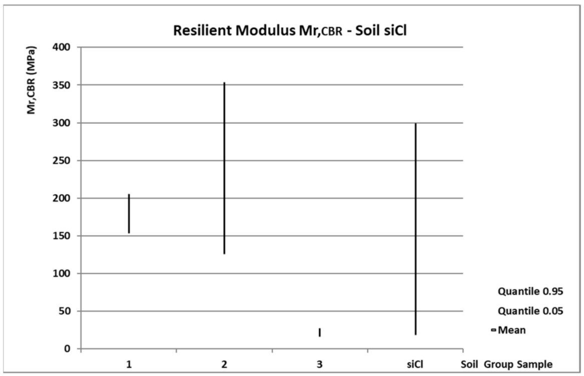

Figure 2. Statistical quantities—mean, 0.05 quantile, 0.95 quantile of $M_{r,CBR}$ for siCl soil.

- Soil N°3—saclSi

The saclSi soil type contains a total of two samplings, see Figure 3. The obtained $M_{r,CBR}$ mean of the entire soil type (obtained by statistical evaluation of all 12 samples) is 122.7 MPa. The coefficient of variation of the entire soil type is 0.59. The minimum value is 46.9 MPa, the maximum value is 261.3 MPa. The 0.05 quantile is 48.8 MPa, the 0.95 quantile is 235.3 MPa for the entire soil type. The results show two distinct subgroups of the values of $M_{r,CBR}$. In the first subgroup, the values of $M_{r,CBR}$ reach up to about 65 MPa; in the second, up to a value of about 260 MPa.

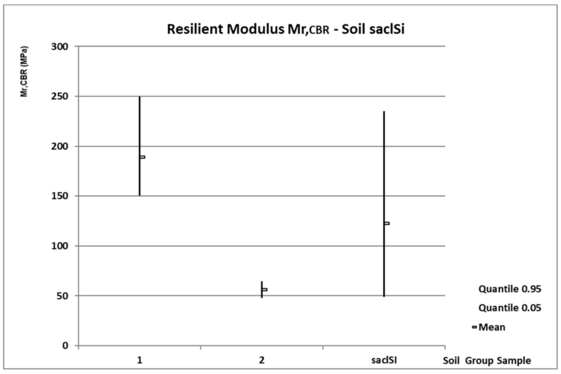

Figure 3. Statistical quantities—mean, 0.05 quantile, 0.95 quantile of $M_{r,CBR}$ for saclSi soil.

- Soil N°4—csaCl

The csaCl soil type contains a total of five samplings, see Figure 4. The obtained $M_{r,CBR}$ mean of the entire soil type (obtained by statistical evaluation of all 30 samples) is 106.9 MPa. The coefficient of variation of the entire soil type is 0.46. The minimum value is 44.2 MPa, the maximum value is 250.8 MPa. The 0.05 quantile is 51.8 MPa, the 0.95 quantile is 205.7 MPa for the entire soil type. The results show three distinct subgroups of the values of $M_{r,CBR}$. In the first subgroup, the values of $M_{r,CBR}$ reach up to about 55 MPa; in the second, up to a value of about 150 MPa; in the third, up to a value of about 250 MPa.

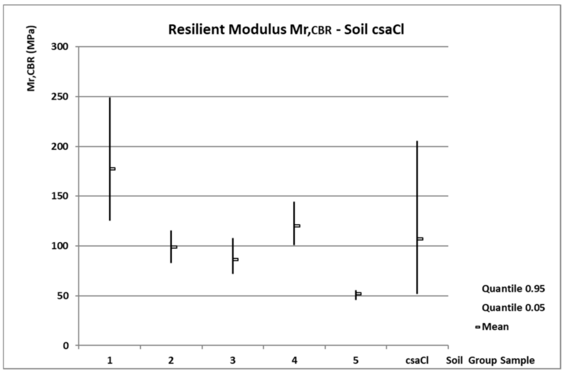

Figure 4. Statistical quantities—mean, 0.05 quantile, 0.95 quantile of $M_{r,CBR}$ for csaCl soil.

- Soil N°5—sagrSi

The sagrSi soil type contains a total of six samplings, see Figure 5. The obtained $M_{r,CBR}$ mean of the entire soil type (obtained by statistical evaluation of all 36 samples) is 101.8 MPa. The coefficient of variation of the entire soil type is 0.78. The minimum value is 20.8 MPa, the maximum value is 330.7 MPa. The 0.05 quantile is 24.1 MPa, the 0.95 quantile is 271.3 MPa for the entire soil type. The results show three distinct subgroups of the values of $M_{r,CBR}$. In the first subgroup, the values of $M_{r,CBR}$ reach up to about 90 MPa; in the second, up to a value of about 140 MPa, in the third, up to 380 MPa.

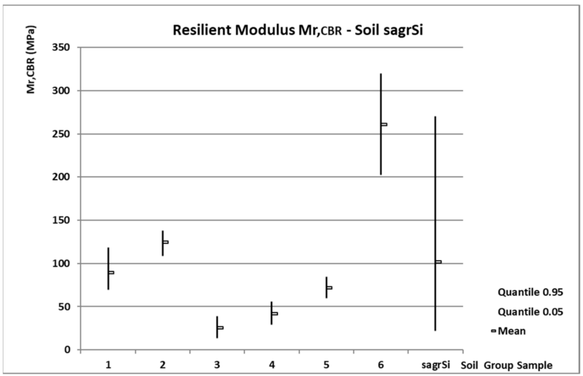

Figure 5. Statistical quantities—mean, 0.05 quantile, 0.95 quantile of $M_{r,CBR}$ for sagrSi soil.

- Soil N°6—grsaCl

The grsaCl soil type contains a total of four samplings, see Figure 6. The obtained $M_{r,CBR}$ mean of the entire soil type (obtained by statistical evaluation of all 24 samples) is 107.9 MPa. The coefficient of variation of the entire soil type is 0.82. The minimum value is 41.8 MPa, the maximum value is 374.9 MPa. The 0.05 quantile is 44.0 MPa, the 0.95 quantile is 310.7 MPa for the entire soil type. The results show two distinct subgroups of the values of $M_{r,CBR}$. In the first subgroup, the values of $M_{r,CBR}$ reach up to about 90 MPa; in the second, up to a value of about 560 MPa.

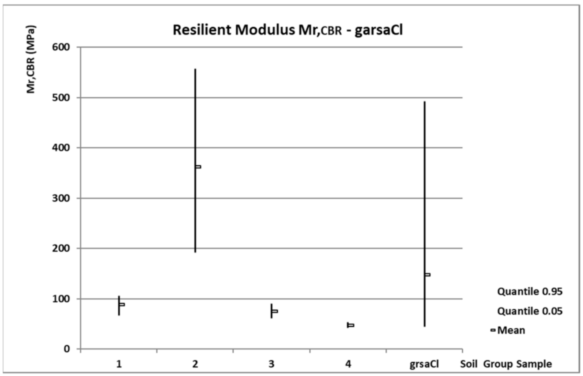

Figure 6. Statistical quantities—mean, 0.05 quantile, 0.95 quantile of $M_{r,CBR}$ for grsaCl soil.

- Soil N°7—siSa

The siSa soil type contains a total of 10 samplings, see Figure 7. The obtained $M_{r,CBR}$ mean of the entire soil type (obtained by statistical evaluation of all 60 samples) is 153.4 MPa. The coefficient of variation of the entire soil type is 0.67. The minimum value is 23.1 MPa, the maximum value is 451.3 MPa. The 0.05 quantile is 29.9 MPa, the 0.95 quantile is 357.6 MPa for the entire soil type. The results show four distinct subgroups of the values of $M_{r,CBR}$. In the first subgroup, the values of $M_{r,CBR}$ reach up to about 55 MPa; in the second, up to about 180 MPa; in the third, up to 245 MPa; and in the fourth, up to 675 MPa.

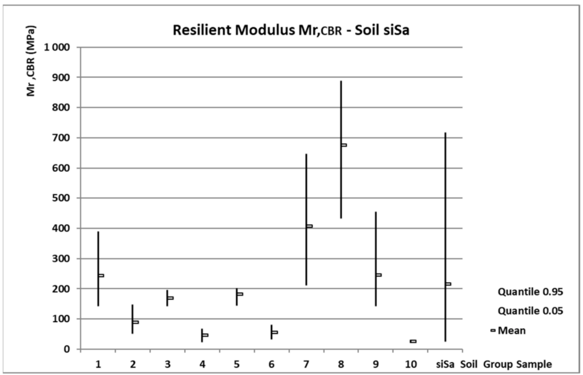

Figure 7. Statistical quantities—mean, 0.05 quantile, 0.95 quantile of $M_{r,CBR}$ for siSa soil.

- Soil N°8—grsiSa

The grsiSa soil type contains two samplings only, see Figure 8. The obtained $M_{r,CBR}$ mean of the entire soil type (obtained by statistical evaluation of all 12 samples) is 116.9 MPa. The coefficient of variation of the entire soil type is 0.24. The minimum value is 67.4 MPa, the maximum value is 168.7 MPa. The 0.05 quantile is 74.6 MPa, the 0.95 quantile is 159.3 MPa for the entire soil type.

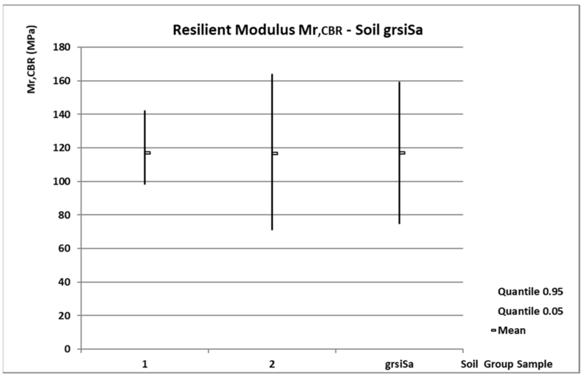

Figure 8. Statistical quantities—mean, 0.05 quantile, 0.95 quantile of $M_{r,CBR}$ for grsiSa soil.

- Soil N°9—siGr

The siGr soil type contains four samplings, see Figure 9. The obtained $M_{r,CBR}$ mean of the entire soil type (obtained by statistical evaluation of all 24 samples) is 32.2 MPa. The coefficient of variation of the entire soil type is 0.60. The minimum value is 9.0 MPa, the maximum value is 79.9 MPa. The 0.05 quantile is 10.7 MPa, the 0.95 quantile is 64.0 MPa for the entire soil type. The results show two distinct subgroups of the values of $M_{r,CBR}$.

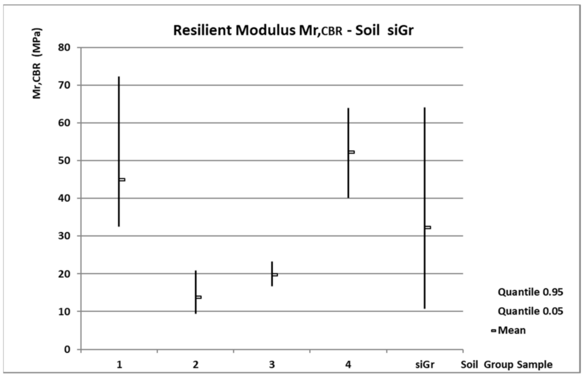

Figure 9. Statistical quantities—mean, 0.05 quantile, 0.95 quantile of $M_{r,CBR}$ for siGr soil.

The results of the statistical analysis show a high variability of the resilient modulus $M_{r,CBR}$. Moreover, intervals of possible values overlap each other, see Figure 10. As result, the representative estimates of $M_{r,CBR}$ for the individual soil types cannot be determined.

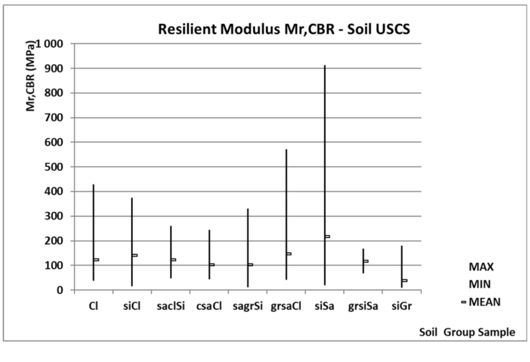

Figure 10. $M_{r,CBR}$ intervals for all soil types.

The high variability of $M_{r,CBR}$ was analyzed and the essential parameters of individual samples, such as humidity, maximum dry density, and plunger stress during the cyclic test, were monitored within individual soil types. The real humidity and the maximum dry density did not differ much from the set optimum humidity and the maximum dry density according to Proctor Standard energy. These parameters were therefore not further examined. On the contrary, the influence of the plunger stress values from the last cycle on variability of $M_{r,CBR}$ was found interesting.

3.2. Results of Plunger Stress in CBR Cyclic Test Analysis

The values of the plunger stress from the last loading cycle were compared with the stress limit value of the soils by Terzagi's theory, according to which the maximum load bearing capacity ranges between 150 and 650 kPa based on the soil type

- Soil N°1—Cl

The soil type contains a total of 10 samplings and 60 samples tested. Over a half, 42 in a total, were cycled at a stress higher than 500 kPa. In the statistical analysis, the samples were divided into two subgroups by the values of $M_{r,CBR}$, which at the same time correspond to the stress limit of 500 kPa. The first subgroup, which was cycled at stresses up to 500 kPa, shows lower values of the moduli, the mean of $M_{r,CBR}$ equal to 77.2 MPa, as well as a smaller variability. The second subgroup, where the samples were cycled at a stress higher than 500 kPa, shows high variability in values of the moduli. The maximum stress was observed in sample 4/19; it was 2202.8 kPa and $M_{r,CBR}$ reached 300.2 MPa.

- Soil 2—siCl

The soil type contains a total of three samplings and 18 samples tested. A total of 12 samples were cycled at a stress higher than 500 kPa. In the statistical analysis, the samples were divided into two subgroups by the values of $M_{r,CBR}$, which in this soil type correspond to the stress limit of 500 kPa. The first subgroup, which was cycled at stresses up to 500 kPa, shows lower values of the moduli, the mean of $M_{r,CBR}$ equal to 21.9 MPa, as well as a smaller variability of their occurrence. The second subgroup, where the samples were cycled at a stress higher than 500 kPa, shows high variability in values of the moduli. The maximum stress was observed in sample 12/11; it was 1986.3 kPa and $M_{r,CBR}$ reached 285.9 MPa.

- Soil 3—saclSi

The soil type contains a total of two samplings and 12 samples tested. Six samples were cycled at a stress of 600–800 kPa and six samples at higher stress. In the statistical analysis, the samples were divided into two subgroups by the values of $M_{r,CBR}$, which correspond to the stress limit up to 800 kPa. The first subgroup, which was cycled at stresses up to 800 kPa, shows lower values of the moduli, the mean of $M_{r,CBR}$ equal to 65 MPa, and there is a smaller variability. The second subgroup, where the samples were cycled at a stress higher than 900 kPa, shows high variability in the values of the moduli; the standard deviation was 38.62. The maximum stress was observed in sample 14/5; it was 3514.1 kPa and $M_{r,CBR}$ reached 214 MPa.

- Soil 4—csaCl

The soil type contains a total of five samplings and 30 samples tested. Eight samples were cycled at a stress of 630 kPa, 17 samples at a stress from 630 to 850 kPa, and six samples at higher stresses. In the statistical analysis, the samples were divided into two subgroups by the values of $M_{r,CBR}$, which also here correspond to the stress limit. The first subgroup, which was cycled at stresses up to 630 kPa, shows lower values of the moduli, the mean of $M_{r,CBR}$ equal to 51.8 MPa, and there is a smaller variability. The second subgroup, where the samples were cycled at a stress from 630 to 850 kPa, shows higher variability in the values of the moduli. The mean of $M_{r,CBR}$ in the second subgroup is 101.9 MPa. The third subgroup, where the samples were cycled at a stress over 850 kPa, shows the highest variability in the values of the moduli. The maximum stress was observed in sample 16/9; it was 1229.0 kPa and $M_{r,CBR}$ reached 244.8 MPa.

- Soil 5—sagrSi

The soil type contains a total of six samplings and 36 samples tested. A total of 24 samples were cycled at a stress up to 600 kPa, six samples at 950 kPa, and six samples at stress up to 1250 kPa. In the statistical analysis, the samples were divided into three subgroups by the values of $M_{r,CBR}$, and this division is reflected in the groups defined by these stresses. The first subgroup, which was cycled at stresses up to 600 kPa, shows the lowest values of the moduli, the mean of $M_{r,CBR}$ equal to 48.6 MPa, as well as smaller variability in the case of three out of four samplings. The second subgroup, where the samples were cycled at a stress from 600 to 950 kPa, shows smaller variability of the moduli. The mean of $M_{r,CBR}$ in the second subgroup is 105.4 MPa. The third subgroup, where the samples were cycled at a stress over 950 kPa, shows the highest variability in the values of the moduli. The maximum stress was observed in sample 27/31; it was 1211.3 kPa and $M_{r,CBR}$ reached 257.3 MPa.

- Soil 6—grsaCl

The soil type contains a total of four samplings and 24 samples tested. Half of the samples were cycled at a stress from 500 to 700 kPa, and the other half at a stress from 700 to 1000 kPa. In the statistical analysis, the samples were divided into two subgroups by the values of $M_{r,CBR}$, which also here approximately corresponds to the stress limit. The first subgroup, which was cycled at stresses up to 700 kPa, shows lower values of the moduli, the mean of $M_{r,CBR}$ equal to 69.26 MPa, and there is a smaller variability. The second subgroup, where the samples were cycled at a stress over 700 kPa, shows higher variability in the values of the moduli. The maximum stress was observed in sample 29/8; it was 999.1 kPa and $M_{r,CBR}$ reached 512.8 MPa.

- Soil 7—siSa

The soil type contains a total of 10 samplings and 60 samples tested. A total of 17 samples were cycled at a stress up to 550 kPa, 18 samples at a stress from 550 to 1000 kPa, six samples between 1000 and 1500 kPa, and 17 samples at higher stresses. In the statistical analysis, the samples were divided into four subgroups by the values of $M_{r,CBR}$, which also here approximately correspond to the stress limit. The first subgroup, which was cycled at stresses up to 550 kPa, shows lower values of the moduli, the mean of $M_{r,CBR}$ equal to 43.0 MPa, and there is a smaller variability. The second subgroup, where the samples were cycled at a stress from 550 to 1000 kPa, shows higher variability in the values of the moduli. The mean of $M_{r,CBR}$ in the third subgroup is 244.8 MPa. The fourth subgroup, where the samples were cycled at a stress over 1500 kPa, shows the highest variability in the values of the moduli. The mean of $M_{r,CBR}$ in the fourth subgroup is 541.6 MPa. The maximum stress was observed in sample 33/2; it was 1935.3 kPa and $M_{r,CBR}$ reached 324.7 MPa.

- Soil 8—grsiSa

The soil type contains only two samplings and 12 samples tested; they were cycled at stresses between 700 and 1635 kPa. In the statistical analysis, the samples were not divided into subgroups by the values of $M_{r,CBR}$. The mean of $M_{r,CBR}$ is 116.9 MPa.

- Soil 9—siGr

The soil type contains a total of four samplings and 24 samples tested. All samples were cycled at a stress lower than 500 kPa. Then, half of them were cycled at a stress up to 200 kPa, the other half from 200 to 500 kPa. In the statistical analysis, the samples were divided into two subgroups by the values of $M_{r,CBR}$, which also here correspond to the stress limit. The first subgroup, which was cycled at stresses up to 200 kPa, shows lower values of the moduli, the mean of $M_{r,CBR}$ equal to 16.8 MPa, and there is a smaller variability. The second subgroup, where the samples were cycled at a stress from 200 to 500 kPa, shows higher variability in the values of the moduli. The maximum stress observed was 495.1 and $M_{r,CBR}$ reached 64.0 MPa.

The interval of plunger stress values at which the appropriate $M_{r,CBR}$ values were determined in individual soil types is shown in Figure 11.

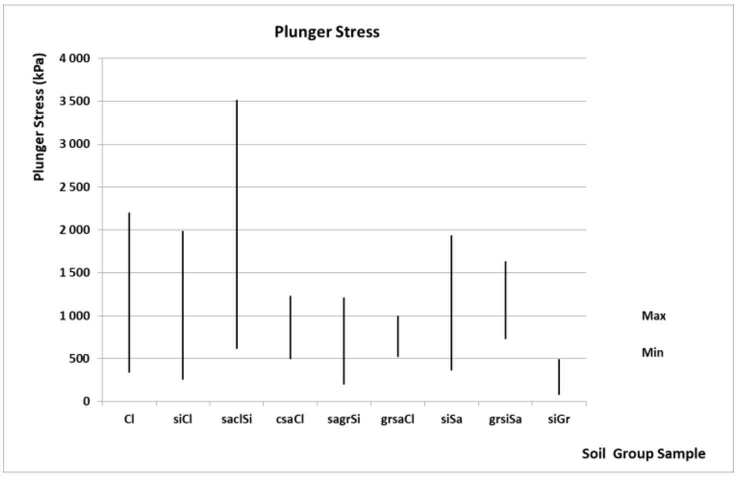

Figure 11. Intervals of plunger stress for all soil types.

The stress values show that the modulus was in most cases determined from a sample disrupted by exceeding the limit values of the bearing capacity; therefore, the basic requirement for the determination of this deformation characteristic of unbound materials using intact samples was not met.

After determining the used stresses range, cyclic tests were reduced based on the stress limit values expected for each soil type. The moduli values after the reduction range between 20 and 200 MPa and the stress during the cyclic test keeps within the permissible limits. The dependence of the mean value of resilient modulus $M_{r,CBR}$ on the applied plunger stress is shown for each soil type in Figure 12.

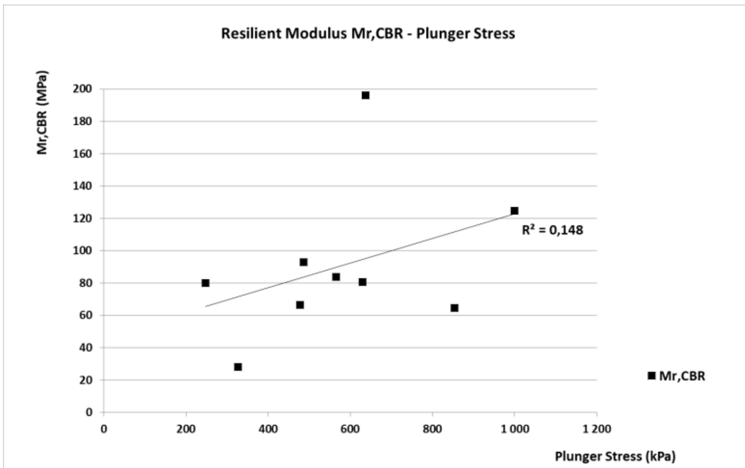

Figure 12. Dependence of the mean values of resilient modulus $M_{r,CBR}$ on the applied plunger stress.

The analysis of plunger stress shows the similar trends in the behavior of all samples. With increasing stress exceeding the load bearing capacity of individual soil types, the variability of $M_{r,CBR}$ as well as its mean value increased. After the reduction, the values of $M_{r,CBR}$ fell into realistic limits. This behavior can be observed in all soil types analyzed.

4. Discussion

In 2008, results of only two unbound materials, specifically grSa coarse-grained material with a maximum dry density of 1670–1720 kgm^{-3} and clay Cl were published [15]. The results valid for both of these materials are comparable to the moduli obtained at Mendel University. The moduli obtained for grSa at Delft University of Technology ranged in intervals from 210 to 900 MPa; MENDELU research found moduli from 100 to 900 MPa. Clay was only tested using one sample with a modulus value of 40 MPa; the occurrence interval of the modulus for Cl ranged from 14 to 429 MPa at MENDELU. Comparing the results, a similar variability of the $M_{r,CBR}$ values obtained from the corresponding test on a cyclic CBR device, can be observed. Despite the small size of the sample and incomplete information on the tests of the Delft research, a good match was found. These values are valid for the state before the plunger stress reduction, i.e., in samples with stress higher than the load bearing capacity limit. The Dutch research did not present the values of the plunger stress applied. With regard to the test methodology going to a depth of 2.5 mm in both studies, high values of plunger stress can be expected.

In 2011, the Dutch team tested unbound subgrade materials, both natural and recycled; their resilient modulus values ranged from 156 to 2600 MPa at stress up to 9000 kPa [32]. The Dutch research team did not address the issue of the overloading of tested samples above their load bearing capacity limit and the results thus correspond to the values measured at Mendel University before the reduction of results obtained at extreme stresses. For base and subgrade materials, the bearing capacity limits will be higher than for the subgrade soils, but even so, the stress in the Dutch research samples was exceeded at least twice [31].

Three studies dated from 2016 to 2019 provide values of resilient modulus of natural subgrade unbound materials obtained from cyclic triaxial equipment.

The study from 2013 [34] analyzed four materials that can be classified as clSa, siSa, grsiSa, and siGr by USCS. Resilient modulus M_r ranged in an interval of 76–159 MPa for soil type clSa, in an interval of 32–111 MPa for siSa, in an interval of 57–148 MPa for grsiSa, and in an interval of 88–141 MPa for siGr. The mean values of M_r from this study and $M_{r,CBR}$ from cyclic CBR after the reduced stress range, were 117 and 67 MPa, respectively, for clSa; 71 and 51 MPa, respectively, for siSa; 102 and 115 MPa, respectively, for grsiSa; 114 and 45 MPa, respectively, for siGr. In all cases, the mean values of the modulus from the cyclic CBR ranged within the interval obtained using the triaxial device.

The studies from 2016 [35,36] examining three soft-grained clay materials and one sandy provided the following occurrence intervals of resilient modulus M_r: 20–134 MPa for Cl, 90–150 MPa for siCl, and 11–84 MPa for csaCl. The occurrence intervals of $M_{r,CBR}$ from cyclic CBR ranged from 37 to 66 MPa for Cl, from 15 to 28 MPa for siCl, and from 44 to 80 MPa for csaCl.

The three previous studies also showed that the resilient modulus values obtained from the triaxial test are in a lower interval than those obtained from the CBR device. As result, the moduli values obtained from the CBR device should be considered as very realistic, especially after the reduction taking into account the material load bearing capacity limit. The differences in mean values obtained from our study were only around 36%. These conclusions are also supported by recent studies [37]. It is also seen, that after the reduction of the extreme plunger stress values, the results obtained at Mendel University are within realistic limits and the $M_{r,CBR}$ estimates can be considered satisfactory.

The problem of the CBR cyclic test can be seen in increase of the plunger stress during the test, which is caused by the test methodology—an unpredictable increase in the stress occurs when the plunger penetrates to the strictly defined depth. As result, the disadvantage of the Dutch procedure with a defined constant penetration is the possible overloading of the sample [31] as well as it is impossible to control the final stress during the cyclic loading.

A solution was found in ensuring that the level of loading during the cyclic test is limited by the maximum stress methodology or is limited by the expected transport loading. The results obtained from the first verifications of this modified procedure at constant stress level at Mendel University of Brno show a more consistent behavior of the modulus leading to the reduction of the $M_{r,CBR}$ variability.

It also reflects the effect of highly plastic clays on flexible behavior as well as the differences between soil types.

5. Conclusions

The existing methodologies for road pavement design are in most cases empirical, or mechanical-empirical, and are not able to directly include the necessary knowledge of the material behavior under representative load conditions. The methodologies presented as mechanistic are based on ideal theories, such as elasticity, and try to adapt reality to theory. The materials of the subgrade soils and pavement structure are subjected to dynamic and repetitive loads of different levels imposed by the transport. In order to take into account the cyclic nature of loading on the material as well as the nonlinear material behavior, many experimental studies have been conducted around the world, both on real-scale models and on samples tested under laboratory conditions, to obtain valuable information about the behavior and deformation to determine the resilient modulus adequately. The concept of the resilient modulus is always associated with the process of repeated loads and depends on the current parameters of the soil—maximum dry density, humidity, compaction method, number and size of loading, and the stress range. Its value is not constant for one soil type, but varies in an interval depending on the test conditions [33], predominantly on the compaction level. Therefore, the method of determining the resilient modulus must take into account the above factors. These requirements are met by resilient modulus obtained from the triaxial test device, but due to its complexity, innovative procedures for its determination are still being searched for [38].

Based on the research conducted at Mendel University of Brno, we can conclude that the methodology of cyclic test using the existing CBR devices could be a very suitable procedure for determining the resilient modulus of subgrade soils after the reduction of plunger stress, especially for roads with lower traffic intensity in regions with high density of these roads where in addition to economic functions, they ensure the access to remote areas. The plunger stress values must not exceed the load-bearing capacity of the material to ensure the correct determination of the modulus.

The advantage of this procedure, unlike the triaxial test, is the same preparation of samples as for the standard CBR test with different amounts of water and at varying degrees of compaction. Thus, it is possible to take into account the influence of humidity and maximum dry density on the modulus value [14], because the load bearing capacity and thus deformation properties of materials are substantially changing.

Author Contributions: L.Š. initiated the investigation, drafted the manuscript and methodology. A.F. carried out the statistical analysis and reviewed the methodology. P.H. reviewed the statistical analysis, carried out the methodology of the manuscript, and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the Technology Agency of Czech Republic, grant number TA01020326.

Acknowledgments: The cooperation of the geotechnical laborator GEOSTAR s.r.o. is highly acknowledged.

Conflicts of Interest: The founding sponsors Technology Agency of Czech Republic and MENDELU had no role in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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