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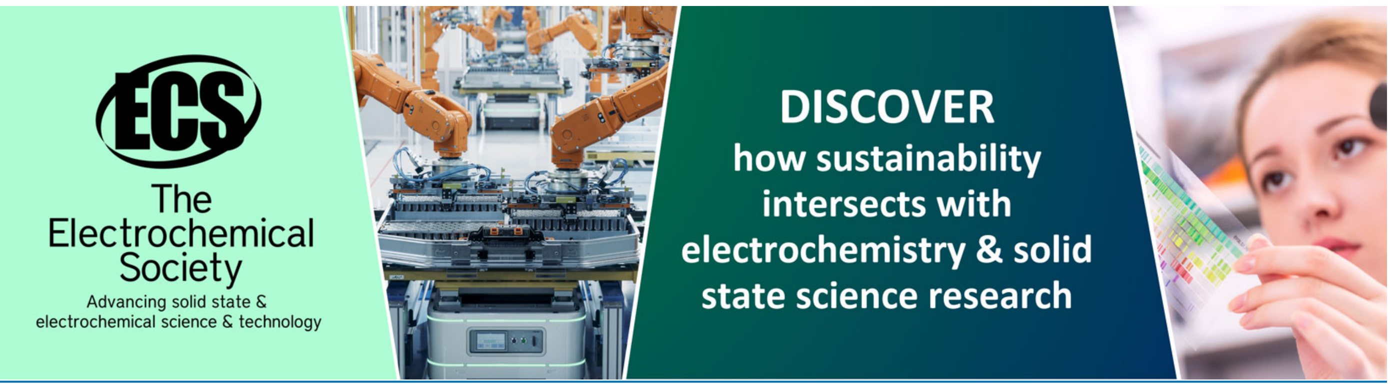

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Determining the track condition using soil properties - part 2

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Abstract. The track condition in conventional ballast construction is decisively determined by the condition of the sub-ballast and the subgrade. An indicator for the assessment of the track condition is the track modulus, which can be calculated by measuring the rail deflection under load or according to the soil properties. The track modulus describes the ratio between vertical loading and elastic deflection of the sleeper support. This is the second of two papers concerning a theoretical approach, which allows the estimation of the track modulus of the soil for the layer arrangement of stiff on soft soil layers by using a homogeneity parameter. The homogeneity parameter has to be considered, so that the influence of the layer arrangement, the layer depth and the soil properties can be examined. Borings with direct ground exploration results and ground penetrating radar measurements are used to determine the soil condition at the track level. After the allocation of the soil properties to each layer, the cone model is used to calculate the average value of the soil properties. Based on the value of the track modulus of the soil, the track condition can then be determined.

1. Introduction

The theoretical approach described in the first part of the paper were used to estimate the track modulus of the soil by soil properties. The results of the developed approach for 160 bore holes and their subsequent classifications are presented. The borehole data was obtained from the company Ground Control GmbH located in Munich, Germany. Finally, an initial approach to determine a homogeneity parameter is presented to take into account the layer arrangement and stiffness (stiff on soft soil layers) of the track modulus of the soil.

2. Verification of the theoretical approach by evaluating 160 borehole profiles

The method for estimating the track modulus of the soil by using the average values of the soil properties was analysed and verified using data from a total of 160 borehole profiles with a uniform depth of 2 meters [1]. The borehole profiles were created in places where a poor track bed condition had been assumed. The aim of the analysis was to compare the track moduli of the soil values calculated by the measured rail deflection under load and the average soil properties in order to adjust them by means of a homogeneity parameter for the consideration of an inhomogeneous soil layer on the track bed and the influence of the semi-infinite soil layer. Thereby, a distinction for the determination of the homogeneity parameter was made between the layer arrangements of stiff on soft and soft on stiff soil layers. Due to the low number of borehole profiles with the combination type of a soft soil layer on a stiff soil layer, only the borehole profiles of stiff soil layers on soft soil layers were investigated. As a first step, the given boreholes were prepared, with care taken that the information required for the analysis, such as the measured deflection of the rail under load, the drilling diagrams as well as the minimum number of soil layers and the borehole profiles were completely available. In addition, borehole profiles with incomplete data (missing measured rail deflections, missing or incomplete drilling diagrams) were excluded from the analysis. A total of 45 borehole profiles were excluded from the analysis. In the second step, the track moduli of the soil values were calculated (for those borehole profiles which were suitable for analysis) by using the average soil properties [2-4] as well as the measured rail deflections under load according to Zimmermann and Winkler [5, 6]. Subsequently, the boreholes were classified into seven classes: excluded borehole profiles (Class 1), borehole profiles with near homogenous soil conditions (Class 2), borehole profiles that had suspected voids between the sleeper and ballast (Class 3), borehole profiles with large deviations in the calculation results (Class 4), borehole profiles with mixed layer arrangements (Class 5), borehole profiles with the combination of soft soil layers on stiff soil layers (Class 6), and borehole profiles with the combination of stiff soil layers on soft soil layers (Class 7).

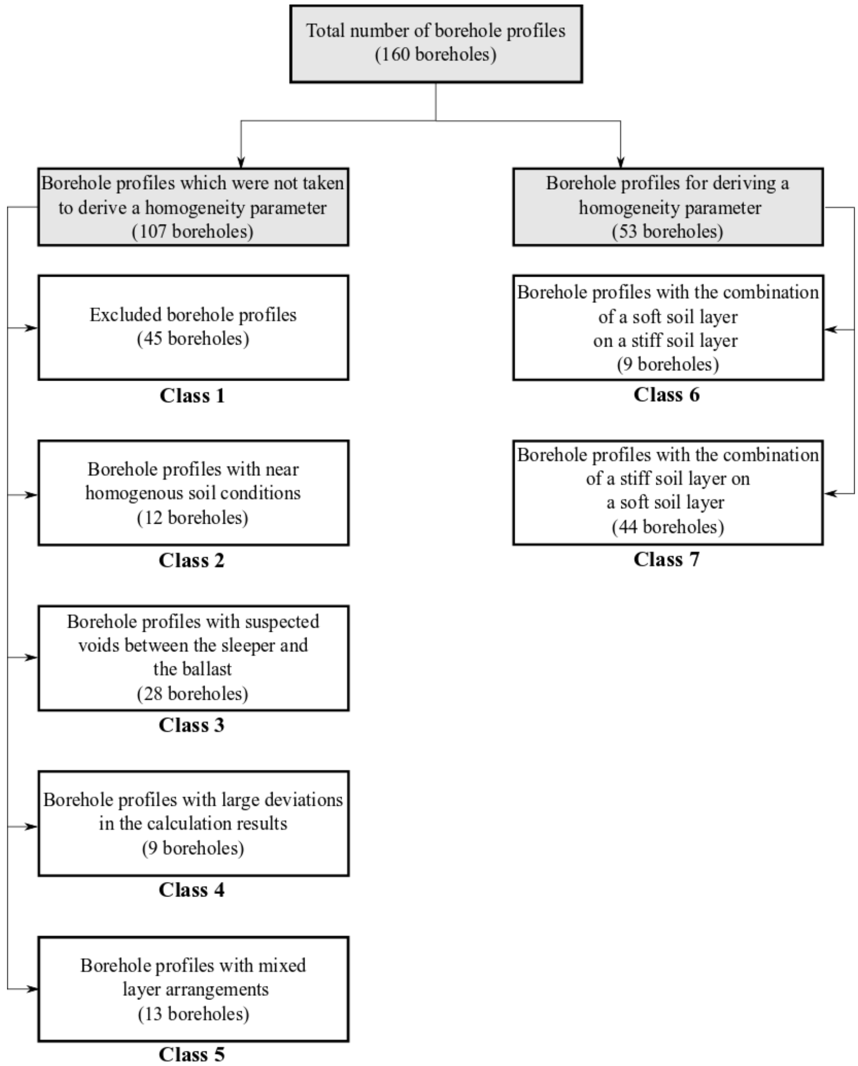

Figure 1. Schematic representation of the classification of the investigated boreholes.

2.1. Class 1: Excluded borehole profiles

Borehole profiles with a missing rail deflection measurement were excluded from the investigation because the track modulus of the soil value according to Zimmermann and Winkler [5, 6] could not be determined without this value. As a result, no comparison of the track modulus values, which serves as a basis for deriving the homogeneity parameter, could be made. Furthermore, those borehole profiles with a given low layer depth were removed from the analysis. In the case of missing or incomplete drilling diagrams of the borehole profiles, it would be necessary to make assumptions regarding their soil properties for the further use of the borehole, which would mean that the calculated track modulus of the soil values, derived from the average density and average Poisson's ratio, could possibly be erroneously estimated.

2.2. Class 2: Borehole profiles with near homogenous soil conditions
Borehole profiles with near homogeneous soil conditions possess almost the same soil properties in all soil layers (excluding the ballast bed). This also means that these soil layers have a near equal load-bearing capacity. Therefore in Class 2, the semi-infinite layer has no influence on the estimated track modulus of the soil. The homogeneity of the soil condition was identified on the basis of the drilling diagrams by considering the number of beats per penetration depth of the penetrometer. The homogeneous soil appeared across the entire depth with nearly equal beats per penetration depth and thereby near equal soil properties (Poisson's ratio and density). In comparing the track modulus values calculated from the Poisson's ratio, the density, and with the track modulus value according to Zimmermann and Winkler [5, 6], a satisfactory result was found for all borehole profiles in Class 2.

2.3. Class 3: Borehole profiles with suspected voids between the sleeper and the ballast
The allocation of the borehole locations on the track with possible voids between the sleepers and the ballast took place primarily by evaluating the rail deflection measured along the track sections, as well as the bearing capacity of the soil determined by the drilling diagrams. The average value of the rail deflection of all boreholes with voids between the sleepers and the ballast was comparatively high and also above the average value of the rail deflection for track sections without voids. Moreover, the assumption of the occurrence of a void on the track was derived by comparing the track modulus values calculated by the measured rail deflection and the soil properties. It was found that the track modulus values calculated with the rail deflection were significantly lower than those estimated with the soil properties. That is to say that although the native soil had a relatively high stiffness (non-cohesive soil), the rail deflection during the deflection measurement was remarkably large, which is in contradiction to a relatively stiff soil on the track. Overall, 28 boreholes with suspected voids at the track were identified.

2.4. Class 4: Borehole profiles with large deviations in the calculation results
Class 4 describes the boreholes where a large discrepancy between the calculated track modulus values was identified. As a result, the track condition could not be determined at the position of these boreholes. In total, there were 9 boreholes where no clear determination could be made with regards to the strongly deviated track modulus values. The reasons for the deviation of the calculated track modulus values are listed in Section 2.3 Part 1.

2.5. Class 5: Borehole profiles with mixed layer arrangements
Boreholes with mixed layer arrangements are those borehole profiles in which the individual soil layers have different degrees of stiffness as well as no specific layer sequence (soft/stiff or stiff/soft). There were a total of 13 boreholes with a mixed layer arrangement profile.

2.6. Class 6: Borehole profiles with the combination of a soft soil layer on a stiff soil layer
The borehole profiles in Class 6 have upper soil layers with a lower load bearing capacity than their lower soil layers. The track moduli of the soil values calculated by rail deflection were lower than the track moduli values estimated by using the soil properties because of the influence of the soft soil layers at ground level and the soft, semi-infinite layer. There were only 9 boreholes along the recorded track sections within this classification. Therefore no further investigations were conducted.

2.7. Class 7: Borehole profiles with the combination of a stiff soil layer on a soft soil layer
In the case of borehole profiles with a stiff soil layer on top of a soft soil layer, the upper soil layers have a higher load bearing capacity than the lower layers of the soil. The track moduli of the soil values calculated by using the rail deflection were larger than those estimated by using the soil properties, due to the influence of the stiff soil layers at the ground level and the stiff, semi-infinite layer. Therefore, a homogeneity parameter for the layer arrangement and depth had to be developed. For Class 7, the number of boreholes amounted to 44.

3. Determination of a homogeneity parameter for the combination of stiff soil layers on soft soil layers

Figure 2 and figure 3 show an overview of the calculated track moduli of the soil values of the boreholes with the combination of stiff soil layers on top of soft soil layers (borehole profile Class 7). It can be stated that in some cases, there are considerable deviations between the track modulus values derived from the soil properties and the track modulus values calculated from the measured rail deflection. These deviations become relatively large in particular as the track modulus values calculated from the measured rail deflection become larger.

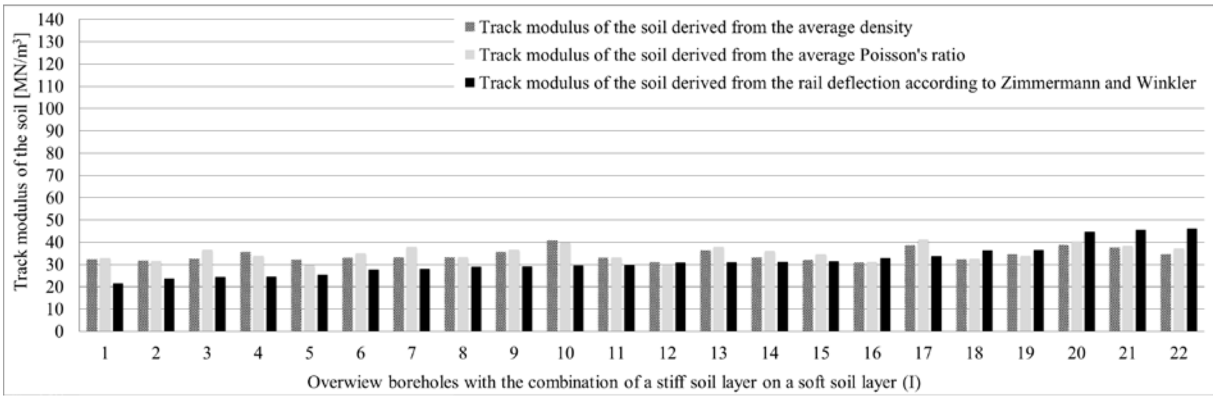

Figure 2. Overview of the calculated track moduli of the soil values for the boreholes with the layer arrangement stiff on soft without correction (Part I).

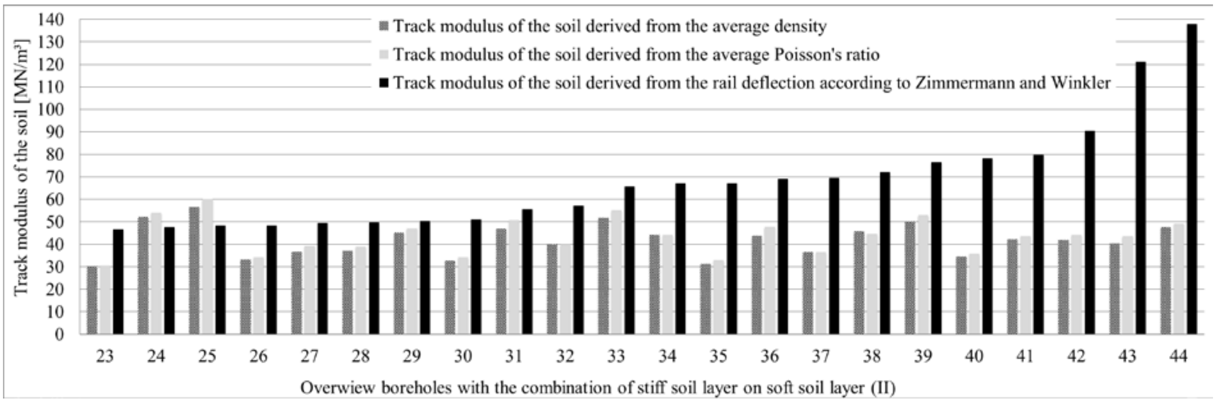

Figure 3. Overview of the calculated track moduli of the soil values for the boreholes with the layer arrangement stiff on soft without correction (Part II).

For the derivation of the homogeneity parameter, the difference between the track modulus values calculated with the soil properties and those measured by rail deflection was analysed by determining the track modulus ratio for each individual borehole. It was recognized from the comparison that in most cases, the difference between the derived track modulus values became larger with decreasing measured rail deflection (cf. figure 3). It was apparent that the difference between the track modulus values continuously increases starting from at approximately the track modulus value (determined from the rail deflection) of 50 MN/m^3 (figure 2 and figure 3). A case study was made when the homogeneity parameter was derived. One homogeneity parameter was then derived for boreholes with a track modulus value starting from the measured rail deflection to 50 MN/m^3 and another parameter was derived for boreholes with a track modulus value starting from the measured rail deflection of more than 50 MN/m^3. In the next step, the relationships between the track modulus ratio and the soil properties of the individual soil layers, the soil layering (in this case a stiff soil layer on top of a soft soil layer), and the layer heights of the native soil were specifically searched for. To take into account the above mentioned parameters, a total of 13 approaches were established within the parameters of the study. Table 1 shows 3 of the 13 variants studied in the framework of the parameter study for taking into account the parameters of the soil properties, soil layering and soil layer height.

Table 1. Compilation of the approaches used to find a homogeneity parameter for stiff soil layers on soft soil layers.

Description of the equation	Variant		
Sum of the stiff soil layers divided by the sum of the soft soil layers with the ballast	$x = \dfrac{\sum \dfrac{\rho_{stiff} \cdot d_{stiff}}{A_{stiff}}}{\sum \dfrac{\rho_{soft} \cdot d_{soft}}{A_{soft}}}$	(3.1)	with ballast
Sum of the layer height of the stiff soil layers minus the sum of the layer heights of the soft soil layers without the ballast	$x = \dfrac{\sum h_{stiff}}{\sum h_{soft}}$	(3.2)	without ballast
Average density (weighted using the layer height) of the stiff soil layers minus the average density (weighted using the layer height) of the soft soil layers with the ballast	$x = \overline{\rho}_{stiff} - \overline{\rho}_{soft}$	(3.3)	with ballast

In order to determine the homogeneity parameter, the ratio between the parameters and the differences between the parameters were widely used. The homogeneity parameter was derived by plotting the resulting track modulus ratios against the values determined by the 13 approaches in a scatter diagram. Subsequently, a linear regression was performed with equation (3.4).

$$y = m \cdot x + b \tag{3.4}$$

The ratios and differences calculated from the 13 approaches were inserted into the derived regression equation (equation of the homogeneity parameter) and therefrom a new, corrected track modulus ratio for each individual borehole was calculated. An example of this approach is presented in figure 4. By multiplying the new track modulus ratios (ratio of the track modulus values calculated by the rail deflection and average soil density) with the track modulus values from the average Poisson's ratio and the average density of each individual borehole, it was finally possible to determine the track modulus values of the Poisson's ratio and the density that match the track modulus value determined from the rail deflection. One of the 13 approaches is described in further detail hereinafter. In this approach, several parameters (soil properties, layer height, and layer arrangement) are simultaneously taken into account. In the approach, the fraction's numerators of the equation (1.13) from the cone model are used. Equation (1.13) refers only to the soil property density and thus only density was used during the derivation of the homogeneity parameter because both of the track modulus values derived from the soil properties were almost the same. The use of the equation (3.1) had the purpose, to simultaneously take into account the parameters of the soil properties and the layer height. Thus, the approach was attempted directly with the cone model. The result of equation (3.1), including the ballast, were formed and subsequently set in a ratio. The formation of the ratios of the sums had the purpose of determining the effect of the stiff and the soft soil layer on the track modulus. Furthermore, the limit set at the beginning of the derivation of the homogeneity parameter was adjusted. It was recognized that the limit of 50 MN/m^3 can only be relevant for the track modulus of the soil values calculated by rail deflection. From figure 3 it can be seen that the track modulus values estimated using the soil properties are generally below 50 MN/m^3. To make the case study applicable to the newly-developed approach according to [2, 4], the limit was reduced from 50 MN/m^3 to 40 MN/m^3. The new limit of the case study is now not related to the track modulus values calculated from the measured rail deflection, but to the track modulus values estimated by soil properties. This enables the adjustment of the track modulus values estimated by the soil properties without knowledge of the rail deflection. Furthermore, the regression equation for the track modulus values over 40 MN/m^3, derived from the soil density, was modified using the software Matlab (Matrix-Laboratory). Equation (3.5) is obtained by the adaptation (figure 5).

$$H(x) = 0.43 \cdot x + 1.006 \tag{3.5}$$

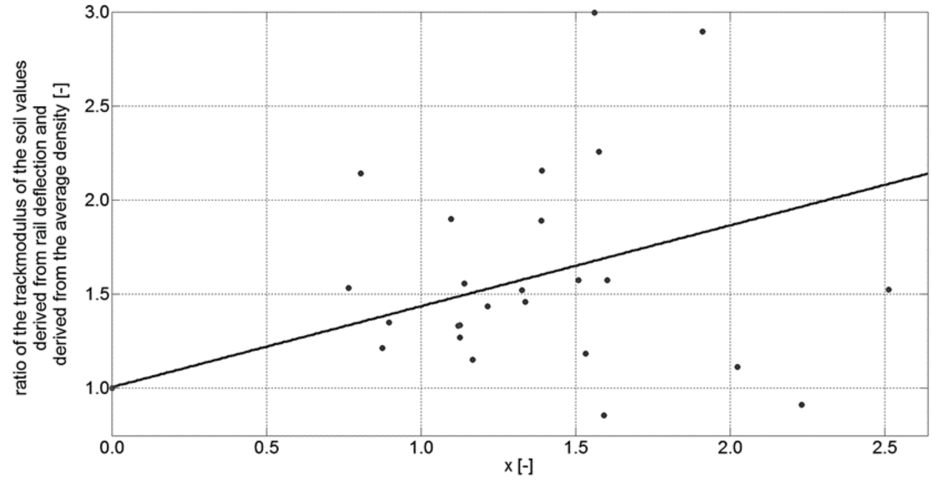

Figure 4. Homogeneity parameter for equation (3.1) and the ratio of the track modulus values.

The y-intercept was thereby set to a value of approximately 1.0. This was assumed on the basis that the track modulus values derived from the Poisson's ratio or from the density up to a value of 40 MN/m^3 are approximately the same as the track modulus values calculated from the rail deflection. Due to this, the track modulus values do not have to be adapted to each other and the homogeneity parameter for this case is H = 1 (see also figure 5). If the calculated track modulus values are more than 40 MN/m^3 based on the soil properties, the homogeneity parameter with the equation (3.6) is used.

$$H(x)=0.43\cdot x+1.006 \tag{3.6}$$

Figure 5 shows the course of the derived function of the homogeneity parameter. Finally, the equation (3.6) has been replaced by a quadratic function because the ratio of the track modulus of the soil values progresses approximately squared with the increasing track modulus values of the soil (see figure 6). A function was determined that ideally had a starting point of 1 and had nearly the same end point compared to a linear function with the value of the track modulus of the soil of 160 MN/m^3. Moreover, a steep increase in the function is also not desired. The homogeneity parameter changes to equation (3.7), which is the final function of the homogeneity parameter, with which the track modulus values derived from the Poisson's ratio and the density were adapted to the track modulus values derived from the measured rail deflection (see also figure 5).

$$H(x) = 0.075 \cdot x^2 + 0.2 \cdot x + 1.126 \times \in (0, 2.5) \tag{3.7}$$

The parameter x describes the quotient of equation (3.1). Figure 6 and figure 7 show the track modulus values corrected by means of the newly set function of the homogeneity parameter. Therefore, the homogeneity parameter was multiplied with the track modulus of the soil, which is determined by soil properties, to calculate the track modulus of the soil for the layer arrangement stiff on soft soil layer.

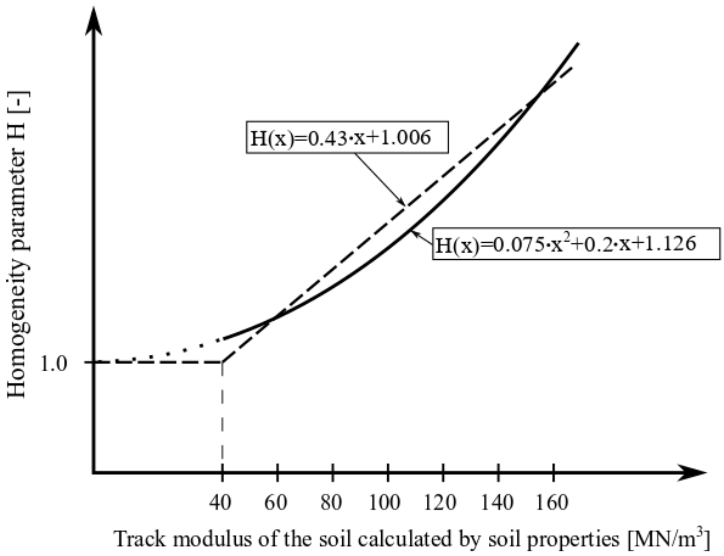

Figure 5. Derived homogeneity parameter function.

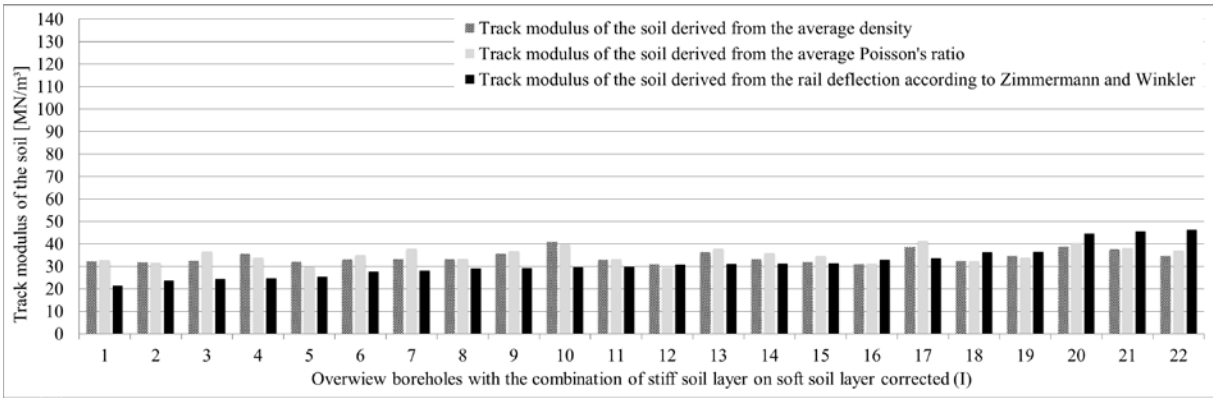

Figure 6. Overview of the calculated track modulus of the soil values of the boreholes with the layer arrangement stiff on soft with correction (Part I).

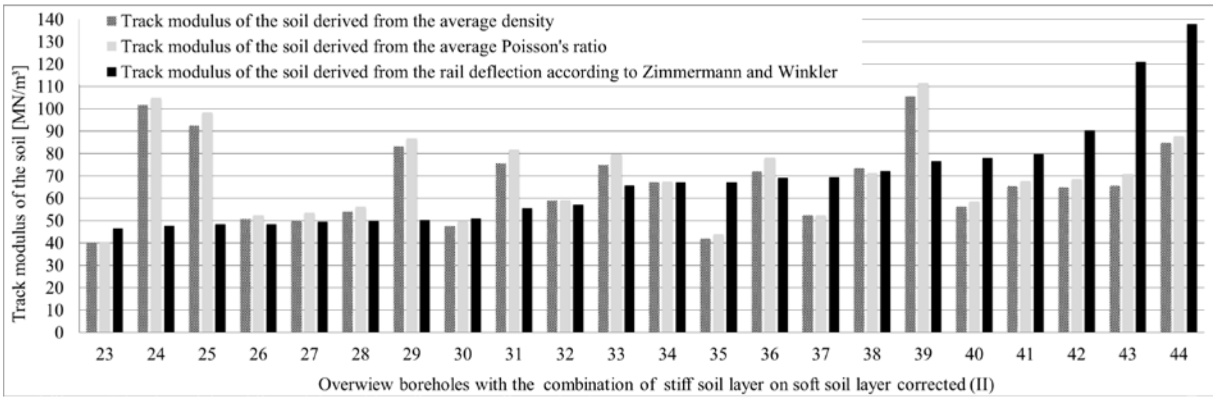

Figure 7. Overview of the calculated track modulus of the soil values of the boreholes with the layer arrangement stiff on soft when using the homogeneity parameter (Part II).

4. Conclusions

In this study, a theoretical approach for determining track conditions using soil parameters was tested for practical application. The average values of the soil properties were calculated using the results of direct ground exploration, ground penetrating radar measurements, and usage of the cone model [7, 8]. Subsequently, the track modulus of the soil was determined by the approach described in the first part of the paper, through which the track condition could be derived. It has been shown that the developed approach can be an alternative to other methods for determining and evaluating the condition of a cross-sleeper track in conventional ballast construction. The application of this approach shows how the values of the soil parameters (Poisson's ratio and density), as well as the layer heights of the native soil, influence the track modulus of the soil. In some cases there were considerable deviations between the track moduli determined by the newly developed approach [2-4] and those calculated by the rail deflection on the basis of the work of Zimmermann and Winkler [5, 6]. By taking into account the track modulus values derived from the rail deflection, the locations with suspected voids between the sleepers and the ballast along the track were able to be recognized in the developed approach. In this parameter study, 44 boreholes of a stiff soil layer on top of soft soil layer were analysed and a homogeneity parameter was derived. The developed homogeneity parameter allows the estimation of the track modulus of the soil for the layer arrangement of stiff on soft soil layers. In order to calibrate the newly-developed approach for general use, it would be advisable to carry out the approach on a larger sample or through simulation methods. An estimation of random errors combined with the introduction of a correction factor is also then be necessary.

On the one hand, the benefit of using the developed method is the determination of the track condition with a completely independent process from the superstructure condition. On the other hand the approach allows the detection of suspected voids between the sleepers and the ballast at the borehole position, depending on the track modulus of the soil or the soil properties. By knowing the soil properties along the railway track by means of ground penetrating radar data, the track condition can be determined with the developed approach. In the end, the method allows for a continuous representation of the track condition (track modulus band) along the railway track.

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