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EXPERIMENTAL ANALYSIS OF STATIC PLATE LOAD TEST ACCORDING TO CZECH, FRENCH AND GERMAN METHODOLOGY

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1. Introduction

The static plate load test (hereinafter also "SPLT") determines the deformation resistance of the railway substructure in the Czech Republic. The main result of its evaluation is the deformation modulus. Its value is determined in the geotechnical survey at different levels of the substructure and is the basic input for the design and dimensioning of sub-ballast layers [1].

Based on the "Fast Railway Connections" development programme approved in 2017 in the Czech Republic, intensive work is currently underway to prepare for the construction of high-speed railway lines in accordance with French technical regulations and standards [2]. At the same time, a joint cross-border section of high-speed line between the Czech Republic and Germany is being prepared [3]. However, there are some secondary problems associated with this, such as SPLT, which is not performed and evaluated in all countries in the same way, but always according to local technical regulations, standards and practices. Therefore, the required values of deformation moduli for Czech high-speed railway lines cannot be simply taken over from French and German technical regulations and standards. For example, Lidmila et al. [4] dealt with the issue of comparing SPLTs according to Czech and German methodology. It was evaluated that the value of the ratio between SPLT results differs by up to 24 % for different materials and the results based on different methodologies cannot be interchanged.

The purpose of this paper is to compare the methods of performing and evaluating the SPLT according to Czech, French and German technical regulations and standards. The comparison is made both from a theoretical and practical point of view to determine the mutual relations between the test procedures according to the Czech methodology.

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2. Methodologies of performing static plate load test

The principle of SPLT is pushing a circular metal plate of a given diameter into the subsoil at prescribed static load while monitoring its displacement. Based on the values of the prescribed static load and the measured values of plate displacement, the deformation characteristics of the subsoil can be determined [1].

2.1. Static plate load test according to the Czech methodology

In the Czech Republic, a circular metal plate with a diameter of 300 mm is used for SPLT. Its procedure is stated in the SŽ S4 regulation [1], Annex 5, and in the ČSN 72 1006 standard [5], Annex B, which states the same procedure.

The load is divided into two cycles, each cycle has four load steps and four unload steps. The maximum contact stress under the plate is 0.20 MPa. Load steps are thus 0.05; 0.10; 0.15 and 0.20 MPa, unload steps are 0.15; 0.10; 0.05 and 0.00 MPa. At each step, the load is kept constant until the plate displacement is stabilized (change in the plate displacement value within one minute is not more than 0.02 mm). After the plate has been pushed into the subsoil, the values of its displacement are noted in each step.

After the test, the graph of the values of plate displacement as a function of the contact stress under the plate is created and, using equations (1) and (2), which are based on the Boussinesq formula, the deformation moduli E_1 and E_2 and their E_2/E_1 ratio are evaluated:

$$E_1 = 1{,}5 \cdot p \cdot r / y_1 \tag{1}$$

$$E_2 = 1{,}5 \cdot p \cdot r / y_2 \tag{2}$$

where:

E_1 is the deformation modulus from the first load cycle [MPa],

E_2 is the deformation modulus from the second load cycle [MPa],

p is the maximum contact pressure under the plate equal to 0.20 [MPa],

r is the radius of the circular metal plate equal to 150 [mm],

y_1 is the difference between the plate displacement values before and after the first load cycle [mm],

y_2 is the difference between the plate displacement values before and after the second load cycle [mm].

2.2. Static plate load test according to the French methodology

A circular metal plate with a diameter of 600 mm is used for the SPLT according to the French methodology and the procedure is in accordance with standard NF P 94-117-1 [6]. A similar procedure is given in the document Mode opératoire CT-2 [7], which briefly describes the procedures of all the most frequently used in-situ tests for traffic structures in France.

The plate is loaded in two cycles, which are not divided into individual steps. In the first cycle, the contact stress under the plate gradually increases from 0 to 0.25 MPa for at least 30 seconds, which is kept constant until the plate displacement is stabilized (the change in the plate displacement value can change by a maximum of 0.02 mm in 15 seconds). Subsequently, the plate is completely unloaded in a maximum of five seconds, and after the plate displacement is stabilized again, the contact stress under the plate starts to increase again at the same speed as in the first load cycle, this time only to 0.20 MPa.

After performing the test, moduli EV_1 and EV_2 including their mutual ratio k are evaluated according to equations (3), (4) and (5), which are based on the Boussinesq formula:

$$EV_1 = 112{,}5/e_1 \tag{3}$$

$$EV_2 = 90/z_2 \tag{4}$$

$$k = EV_2/EV_1 \tag{5}$$

where:

EV_1 is the deformation modulus from the first load cycle [MPa],
EV_2 is the deformation modulus from the second load cycle [MPa],
e_1 is the difference between the plate displacement values before and after the first load cycle [mm],
z_2 is the difference between the plate displacement values before and after the second load cycle [mm].

2.3. Static plate load test according to the German methodology

In Germany, a circular metal plate with a diameter of 300 mm is used for SPLT and the standard DIN 18134 [8] is followed. A similar procedure, which differs only in a few formal respects (eg. limitation of maximum plate displacement or requirements for mutual spacing of the plate, counterweight supports and measuring beam supports), is also stated in the standard ČSN 72 1006 [5], Annex A, which defines the SPLT for road structures in the Czech Republic.

The load is divided into two cycles of at least six load steps and at least three unload steps. The maximum contact stress under the plate in the first cycle is 0.50 MPa, in the second cycle the maximum contact stress under the plate is the same as in the penultimate load step of the first cycle. The load steps should consist of approximately equal intervals, the unload steps are 50%, 25% and 0% of the maximum contact stress under the plate. At each step, the load is kept constant until the plate displacement is stabilized (two minutes after reaching the prescribed value of contact stress under the plate). After pushing the plate into the subsoil, the values of its displacement are recorded in each step.

After the test, the coefficients a_0, a_1 and a_2 are determined for each of the load cycles by the least squares method so that the value of plate displacement and the value of contact stress under the plate in each load step corresponds to equation (6) representing the regression curve of the load cycle. The values at which the plate stress is zero are omitted from the calculation.

$$s = a_0 + a_1 \cdot \sigma + a_2 \cdot \sigma^2 \tag{6}$$

where:

s is the plate displacement [mm],
σ is the contact stress under the plate [MPa],
a_0, a_1, a_2 are the load cycle regression curve parameters [mm, mm·MPa^{-1}, mm·MPa^{-2}].

The deformation moduli from each of the load cycles are then calculated according to equation (7):

$$E_V = 1{,}5 \cdot r/(a_1 + a_2 \cdot \sigma_{max}) \quad (7)$$

where:

E_V is the deformation modulus [MPa],

σ_{max} is the maximum contact stress under the plate [MPa],

r is the radius of the circular metal plate equal to 150 [mm],

a_1, a_2 are the load cycle regression curve parameters [$mm \cdot MPa^{-1}$, $mm \cdot MPa^{-2}$].

3. Results of comparative measurements

For practical comparison of SPLT methodologies, a series of five comparative measurements were performed, from which a total of 30 SPLT results were obtained. To check the uniformity of compaction and homogeneity of the tested subsoil, these SPLTs were further supplemented by dynamic plate load tests using light weight deflectometer (hereinafter "LWD") performed according to SŽ S4 [1], Annex 5. Part of the measurement was performed within the diploma thesis [9]. Performing the SPLT according to the French methodology is shown in *Fig. 1*.

Fig. 1 – Performing the SPLT according to the French methodology

The first two measurements were performed in experimental conditions in the Zbraslav quarry, where in both cases two test layers were made from a crushed stone mixture of the fraction 0/32 (hereinafter "CSM 0/32") and a crushed stone mixture of the fraction 0/63 (hereinafter "CSM 0/63"). Three SPLTs were performed on each of these layers according to individual methodologies.

Another three measurements were performed on constructions of railway lines in the Czech Republic, where the substructures, similarly to the test layers in the Zbraslav quarry, were formed by layers of aggregates of various fractions. In all cases, it was a phase of construction in which the earthworks had already been made, however, the railway superstructure was still not laid. In two cases, the measurements were performed once at the surface of the top sub-ballast layer and once at the subgrade surface. In the third case, the measurement was performed twice at the surface of the top sub-ballast layer, but each time in a different cross-section with a different substructure.

Tab. 1 shows all the results of performed SPLTs. Three SPLT trios were performed on CSM 0/32, five SPLT trios on CSM 0/63, one SPLT trio on a crushed rock of the fraction 0/125 (hereinafter "CR 0/125") and one SPLT trio on soil treated by hydraulic road binders (hereinafter "STH").

When measuring on the railway line in Uničov, a very high value of the deformation modulus from the second load cycle E_2 = 264.7 MPa was found at the subgrade surface (SCH) for the SPLT according to the Czech methodology. In the case of SPLT according to the German methodology, where the regression parameters a_1 and a_2 of load cycles also contribute to the results, the value of deformation modulus from the first load cycle E_{V1} = 196.4 MPa is even higher than the value of deformation modulus from the second load cycle E_{V2} = 168.5 MPa. This was probably an exceptional situation, which was confirmed by the results of LWD tests. Based on this fact, these results cannot be considered as valid and the tested subsoil as homogeneous. When mixing the soil with the binder, areas with a higher proportion of this binder, i.e. local increases in the deformation resistance of the entire material, were probably created. Such a situation can be assessed in such a way that the SPLT according to the Czech methodology was performed on a different subsoil than the SPLT according to the French or German methodology. For this reason, the results of SPLTs performed on STH are not considered as valid and are further omitted from the evaluation of comparative measurements (marked with the symbol * in *Tab. 1*).

4. Results comparison

The values given in *Tab. 1* were statistically evaluated and mutual correlations were sought. *Fig. 2* and *3* show the relationships between the deformation resistance values according to the Czech and French methodology, resp. according to the Czech and German methodology, regardless of the material of the tested layer. The linear curve interpolated between the nine values showed a higher correlation coefficient of linear dependence for the French methodology (R^2 = 0.94) than for the German methodology (R^2 = 0.72).

It is evident from both previous graphs that the highest values according to the Czech methodology are related to the CR 0/125 layer, therefore the influence of the aggregate fraction was monitored in detail in *Fig. 4* and *5* with a focus on CSM 0/32 and CSM 0/63. In both graphs, the interpolated curves for CSM 0/32 are higher than for CSM 0/63. From the point of view of the correlation coefficient, an excellent correlation was reached depending on the Czech and French methodologies (R^2 = 1.00 for CSM 0/32, or R^2 = 0.98 for CSM 0/63) and a larger variance of values when comparing the Czech and German methodology (R^2 = 0.68 for CSM 0/32, or R^2 = 0.90 for CSM 0/63).

Tab. 1 – Summary of results of performed static plate load tests

No.	Location	Methodology	Deformation modulus from the first load cycle [MPa] (E_1, EV_1, E_{v1})	Deformation modulus from the second load cycle [MPa] (E_2, EV_2, E_{v2})	Ratio of deformation moduli from individual load cycles [-] (E_2/E_1, k)
1	Zbraslav quarry (1)	Test layer, CSM 0/32			
		Czech	52.1	91.8	1.8
		French	24.1	73.2	3.0
		German	21.0	78.5	N/A
		Test layer, CSM 0/63			
		Czech	50.8	68.5	1.4
		French	12.7	66.7	5.3
		German	20.4	70.7	N/A
2	Zbraslav quarry (2)	Test layer, CSM 0/32			
		Czech	56.7	96.4	1.7
		French	34.3	77.1	2.2
		German	29.4	104.5	N/A
		Test layer, CSM 0/63			
		Czech	45.6	106.3	2.3
		French	45.1	97.1	2.2
		German	54.7	149.2	N/A
3	Railway line in Soběslav	Subgrade, CR 0/125			
		Czech	114.4	198.5	1.7
		French	121.8	162.7	1.3
		German	140.2	205.8	N/A
		Sub-ballast layer, CSM 0/63			
		Czech	78.9	143.6	1.8
		French	102.6	142.1	1.4
		German	121.9	207.7	N/A
4	Railway line in Uničov	Sub-ballast layer, CSM 0/32			
		Czech	46.1	117.4	2.5
		French	38.9	100.4	2.6
		German	25.9	114.8	N/A
		Subgrade, STH			
		Czech	192.9*	264.7*	1.4*
		French	82.9*	92.5*	1.1*
		German	196.4*	168.5*	N/A
5	Railway line in Brandýs nad Orlicí	Sub-ballast layer, CSM 0/63, km 265.65			
		Czech	40.1	84.4	2.1
		French	47.7	74.8	1.6
		German	55.2	136.7	N/A
		Sub-ballast layer, CSM 0/63, km 265.20			
		Czech	35.9	80.4	2.2
		French	37.8	67.7	1.8
		German	34.7	83.7	N/A

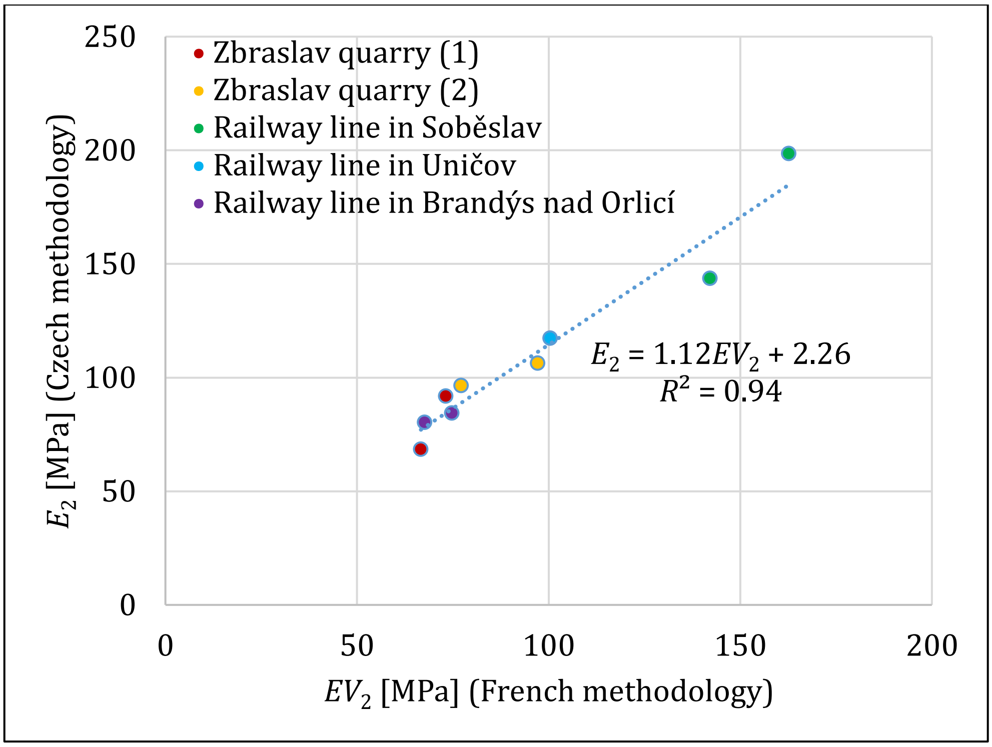

Fig. 2 – Correlation graph of E_2 a EV_2 moduli (Czech and French methodology)

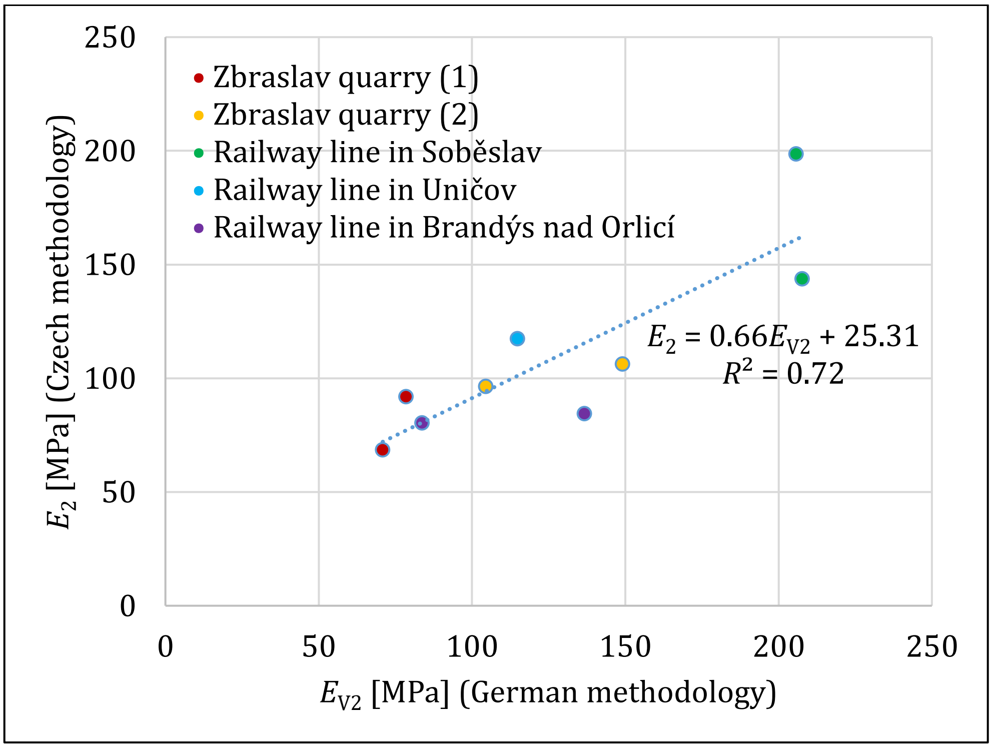

Fig. 3 – Correlation graph of E_2 a E_{V2} moduli (Czech and German methodology)

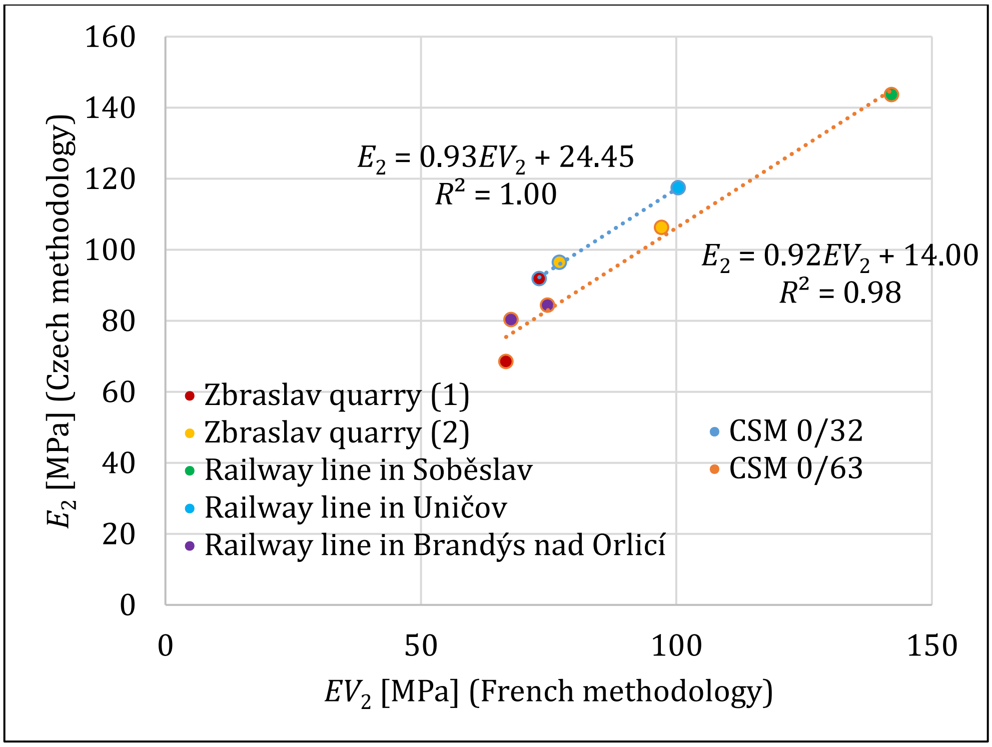

Fig. 4 – Correlation graph of E_2 a EV_2 moduli (Czech and French methodology) for CSM 0/32 and CSM 0/63

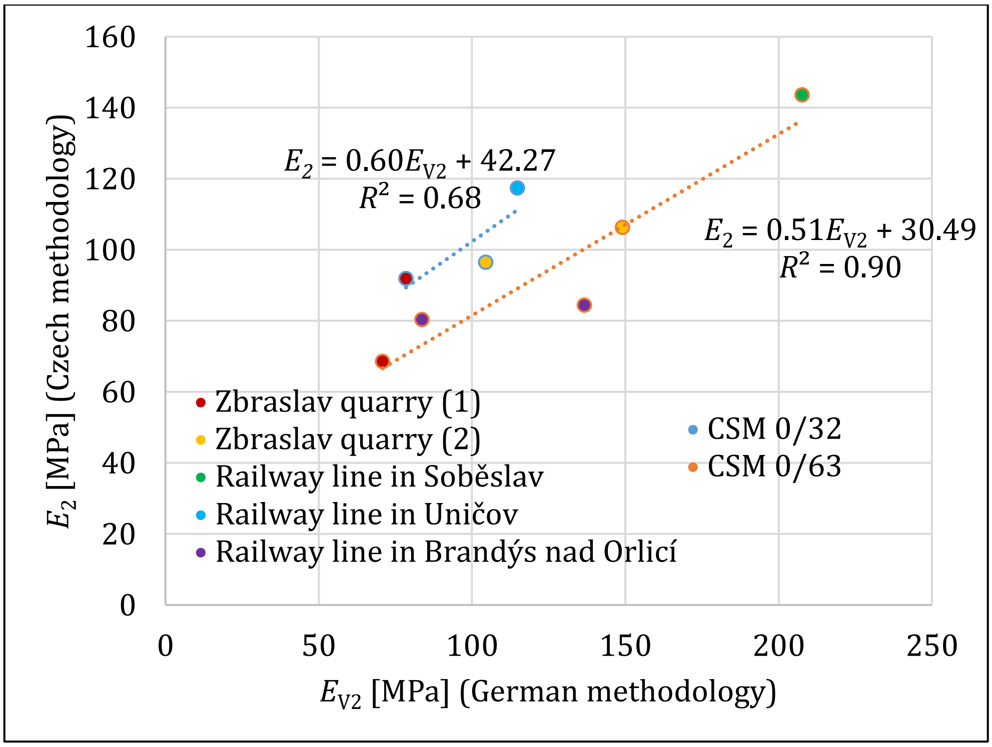

Fig. 5 – Correlation graph of E_2 a E_{V2} moduli (Czech and German methodology) for CSM 0/32 and CSM 0/63

The results of the deformation modulus from the first load cycle were also compared with each other, regardless of the material. *Fig. 6* shows the dependence between the values according to the Czech and French methodology (correlation coefficient R^2 = 0.74), *Fig. 7* between the values according to the Czech and German methodology (correlation coefficient R^2 = 0.73). The values of correlation relevancy thus turned out to be very similar.

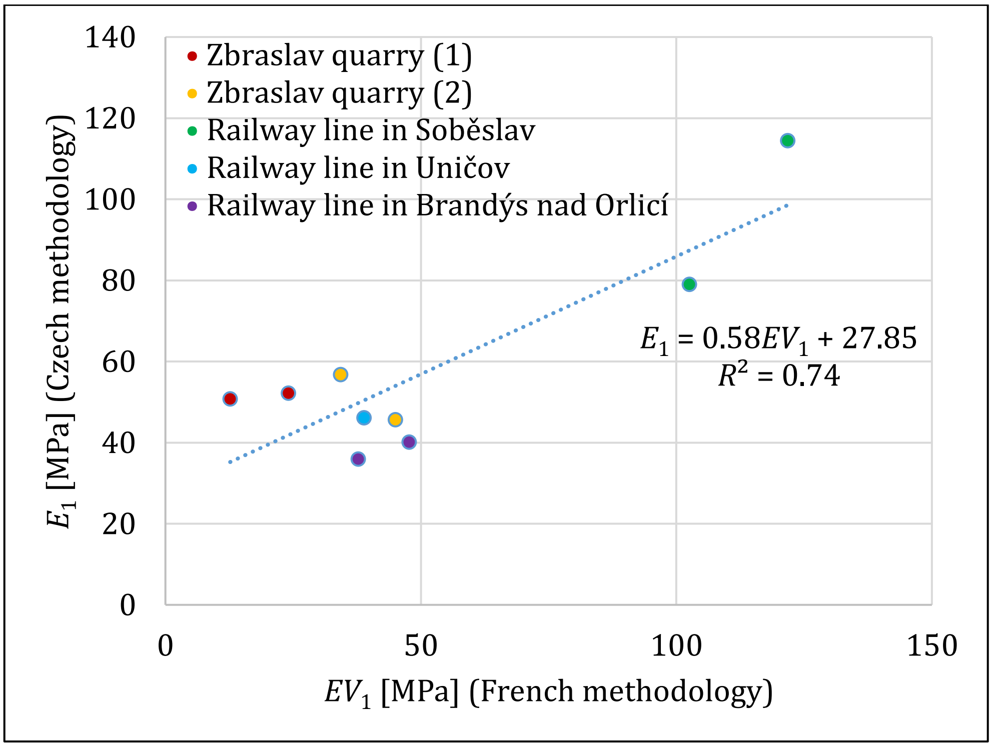

Fig. 6 – Correlation graph of E_1 a EV_1 moduli (Czech and French methodology)

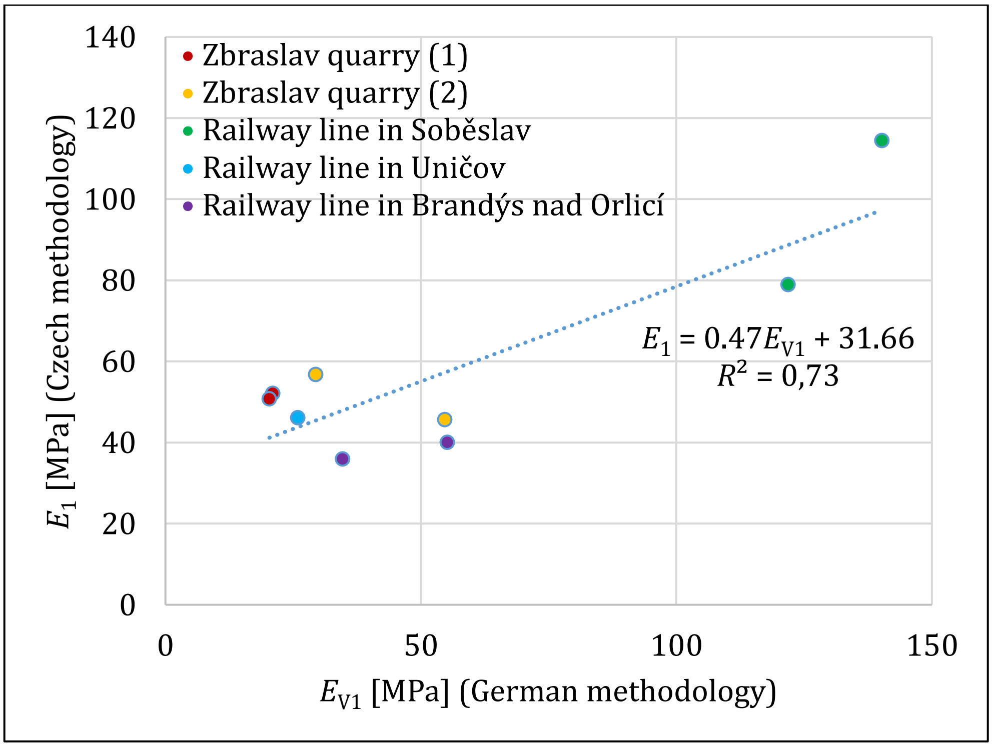

Fig. 7 – Correlation graph of E_1 a E_{V1} moduli (Czech and German methodology)

When comparing the values of the correlation coefficient of linear dependence based on the values from the second and the first load cycle between the Czech and German methodology, the values are very similar (R^2 = 0.72 and R^2 = 0.73), and while comparing the Czech and French methodology, the values differ (R^2 = 0.94 and R^2 = 0.74). This can be explained by the fact that in the first load cycle, the load is initially applied to the tested subsoil during which a good contact is ensured between the plate and the monitored layer. In the first cycle, the effect of local inaccuracies is manifested, which is significantly reduced in the second load cycle, especially when using a plate of a larger radius.

5. Discussions

Methodology and thus also results of SPLTs according to the Czech, French and German methodology differs significantly. While in the Czech methodology the same value of the maximum contact stress under the plate is used in the first and also in the second load cycle (0.20 MPa), in the French and German methodologies these values in the first and in the second cycle differ. In the case of French methodology, the maximum contact stress under the plate of 0.25 MPa is applied in the first cycle and 0.20 MPa in the second cycle, in the case of German methodology 0.50 MPa and 0.42 MPa. If we consider the size of the plate surface and the value of the maximum contact stress, the counterweight needs to be 5 times heavier for SPLT carried out according to the French methodology than in the case of SPLT according to the Czech methodology, for SPLT according to the German methodology this ratio is 2.5.

The results of tests performed at STH were set aside from the evaluation of SPLT results due to the detected inhomogeneity of the material in the monitored location. However, the fact is also that STH is very different in character from other tested materials because compared to CSM and CR it is a material mixed with other binders. However, as improved soils and stabilization are often used in the construction of railways, it is desirable to establish correlations for these materials as well.

For the relationship between the values of deformation modulus from the second load cycle of SPLT according to the Czech and French methodology and according to the Czech and German methodology, linear trend lines were created and their equations were determined, which are together with squares of their correlation coefficients clearly shown in *Tab. 2*. The table contains an illustrative example. If the requirement of foreign regulations for the value of the deformation modulus EV_2, resp. E_{V2}, was 80 MPa, this value can be understood as the values of the deformation modulus E_2 calculated here.

Tab. 2 – Example of calculation of the required value of the deformation modulus E_2 from the values given in foreign regulations according to the obtained equations

Material	Equation of linear trend line	R^2 [-]	EV_2, resp. E_{V2} [MPa]	E_2 [MPa]
Comparison of SPLT according to the Czech and French methodology				
CSM 0/32	$E_2 = 0.93EV_2 + 24.45$	1.00	80	98.6
CSM 0/63	$E_2 = 0.92EV_2 + 14.00$	0.98	80	87.7
independently	$E_2 = 1.12EV_2 + 2.26$	0.94	80	92.0
Comparison of SPLT according to the Czech and German methodology				
CSM 0/32	$E_2 = 0.60E_{V2} + 42.27$	0.68	80	90.3
CSM 0/63	$E_2 = 0.51E_{V2} + 30.49$	0.90	80	71.3
independently	$E_2 = 0.66E_{V2} + 25.31$	0.72	80	78.1

However, it should be noted that these equations and correlation coefficients are based only on the set of found values, i.e. nine trios of SPLTs performed on three different materials. Other materials, especially those with lower deformation resistance, were not observed. In this situation, it can be assumed that the above equations can be applied as initial relationships in cases where the required values of moduli EV_2 and E_{V2} approximately correspond to the values specified in this article and when the substructure is made of the same materials.

6. Conclusions

The aim of the research was to perform comparative SPLTs according to the Czech, French and German methodology, to evaluate the values of deformation modulus and to express the mutual relations between their values on selected materials used in the railway substructure in the Czech Republic. A total of 30 SPLTs were performed on 4 different materials.

Based on the comparison of values of the deformation modulus from the second load cycle, a positive correlation was found between the results according to the Czech and French methodologies. A better correlation was found when comparing the values found on the same aggregate fraction (R^2 = 0.98 – 1.00) than when evaluating regardless of the aggregate fraction (R^2 = 0.94). In the case of comparison of values according to the Czech and German methodology, a good correlation of values was found on CSM 0/63 (R^2 = 0.90), while on CSM 0/32 only R^2 = 0.68, which may be affected by a small data set (three values only).

Additionally, the correlation of the values of deformation modulus from the first load cycle was evaluated, which, however, in accordance with the assumption, was not higher due to a larger variance of values.

As part of the research project, further comparative static load tests will be performed in the years 2022 – 2023, which will be used to refine and expand mutual correlations.

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