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DETERMINATION OF THE CORRELATION DEPENDENCE BETWEEN STATIC AND DYNAMIC MODULUS OF DEFORMATION OF THE GRANULAR SUB-BALLAST LAYERS

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Abstract

Technological procedures related to the possession of tracks are often under heavy time constraints. Therefore, the attempts to apply dynamic load tests in the process of diagnostics of implemented construction works on modernised sections of railway infrastructure are increasingly frequent. When modernising constructing traffic constructions – even if dealing with technological works not related to the possession of tracks – it is often necessary to ensure a rapid progression of individual work activities or to carry out diagnostics tests in the sections with limited access to mechanisation. This test is reasonably suitable to detect critical areas not compliant with deformation standards. The combination of dynamic load tests with the static load test in these areas could, therefore, prove to save time as well as financial expenses spent on construction works inspection diagnostics. Based on the above-mentioned reasons, the presented article is focused on the analysis of set values of the dynamic modulus of deformation, obtained through light dynamic load test LDD 100, and the static modulus of deformation obtained by employing the test procedure set out in the methodology regarding the sub-ballast layers diagnostics used for German railways (DIN 18 134) and the methodology used for the Railways of the Slovak Republic (regulation ŽSR TS4).

Keywords:

Static load test;
Dynamic load test;
Sub-ballast layers
Crushed aggregate;
Correlations.

1 Introduction

Being a part of the overall economy, transport creates the necessary conditions and prerequisites for the standard and efficient functioning of the economic system and society as a whole. To meet the transport and traffic needs of the state on the required quantitative and qualitative level, it is necessary not only to possess suitable transport systems but also to organise, manage and financially support them to ensure their long-term usability, functionality and reliability.

Railway infrastructure, the indispensable part of transport services and a vital player in the transport requirements of the state as well as business entities faces ever-increasing demands, caused by the need to improve its safety along with reliability and environ-mental compatibility. Even the Slovak Republic reassesses the significance of Railways of the Slovak Republic's (ŽSR) infrastructure, enhancing the usability of its overall network, for example by modernising and reconstructing its main lines which are part of the trans-European corridors [1].

An essential part of such modernisation and reconstruction of railways is the control diagnostics of the implemented construction works and operational diagnostics exercised after they were commissioned. The beginnings of this research, focused on monitoring the deformational (mechanical) properties of different soil types, were defined by Boussinesq [2]. Nowadays, his results form the basis of test methods that assess the deformation resistance of the structural layers of the transport structures. For example, experimental measurements assessing the deformation resistance of structural layers, and implemented by static load tests, are presented in [3] and structural layers reinforced by geosynthetics in [4]. However, when increasing the deformation resistance of the whole structure, the results of the tests addressed in the article indicate a limited contribution of geosynthetics. A significant increase in the structure's deformation resistance has only been demonstrated for certain types of geosynthetics and when dealing with subgrade with very little deformation resistance covered by a 200 mm thick sub-ballast layer. The implementation of static load tests on the clayed sand subgrade was presented in the paper [5]. As a result, a simple method for determining the deformation resistance of unsaturated subgrade is provided. Experimental measurements using static load tests have also been performed on coarse-grained soil in publication [6]. As a result of the research, an equation was pro-posed to predict the deformation resistance of a two-layered structure of coarse-grained soils. At the same time, the dynamic load tests were used to monitor the behaviour of in-appropriately grained calcareous and silica sand in paper [7]. The result of this paper is the behavioural description of very loose, loose, medium dense and dense sands during their dynamic load. The limit of the influence of the dynamic load test has been determined. The comparison of different construction designs of equipment needed to perform dynamic load tests is presented in [8]. The option to determine the quality of aggregate compaction using a light dynamic impact load test along with the device for soil stiffness gauge was assessed and presented in the paper [9]. The option to use a dynamic load test instead of a static load test to assess the deformation characteristics of cellular concrete is presented in the paper [10]. Correlations between static and dynamic modulus of deformation, determined for different types of soils, were presented in [11], [12] and [13]. The application of the first, simplified numerical model of layered half-space was published in [14]. Numerical modelling of the transport structures' behaviour under different loads is currently based on the application of non-linear analysis using 3D elements [15-21].

Following the qualitative diagnostics of railways, members of the Department of Railway Engineering and Track Management (DRETM) of the Faculty of Civil Engineering at the University of Žilina (UNIZA) monitor the deformation characteristics of the trackbed [22], [23], or geometrical parameters of the track [24], [25]. The control diagnostics of the construction works implemented on modernised or reconstructed railways often faces the problem of difficult access of counter load on the measurement–diagnostics site, due to e. g. existing underground services, the impossibility of counter load's access to the construction pit, the availability of counter load for the execution of static tests (rapid sequence of work activities), blocking the access road during testing, etc. These problems invite the possibility to utilise dynamic load test using the LDD 100 (so-called light dynamic plate), or its suitable combination with the static load test during the process of control diagnostics of the ongoing construction works.

The purpose of the submitted article was to establish the correlation dependence between the dynamic load test performed by the LDD 100 device and the static load test performed by two test procedures (ŽSR methodology [26] and the DB A.G methodology [27]) on a realistic experimental field, using a sufficient set of experimental measurements. During these measurements, the influence of the thickness of the structural layer of crushed aggregate fr. 0/31.5 mm on the achieved static E_s and dynamic E_{vd} modulus of deformation was also assessed.

2 Materials and Methods

To determine the correlation dependence between the static and dynamic modulus of the granular sub-ballast layers, an experimental field, characterising the standard constructional composition of the sub-ballast layer was built in the UNIZA campus, in the sector used for assessing the deformation characteristics of building materials – Fig. 1 (left).

Fig. 1: Sector for assessing the deformation characteristics of building materials (left) and construction of the structural layer of the experimental field (right).

The main part of the above-mentioned sector is a steel frame with a movable crossbeam, which, when implementing the static load tests, can be used as a counter load. The experimental field (Fig. 2) was built at the bottom part of the sector (Fig. 1 on the left, before construction, the part was protected from weather conditions with foil). The construction process of one of the experimental field's structural layers is shown in Fig. 1 (right).

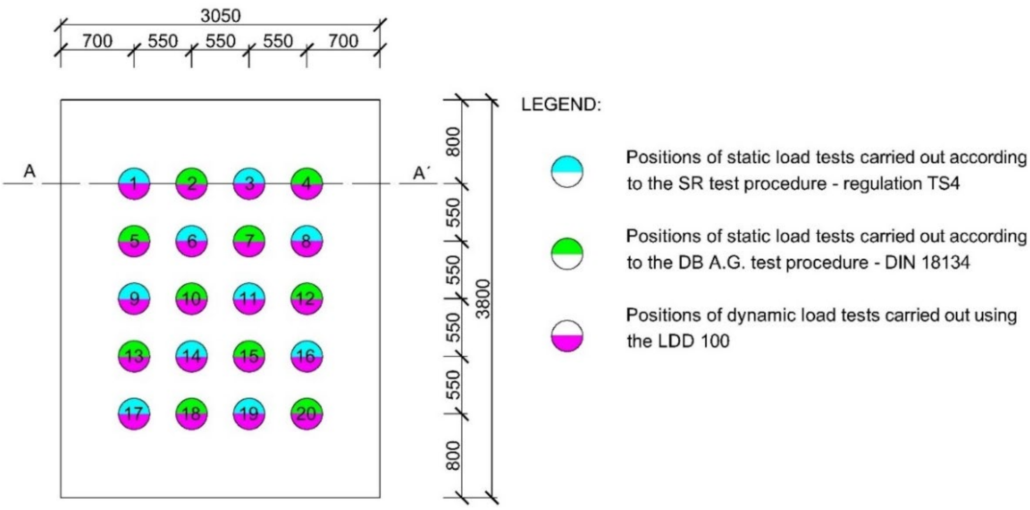

Fig. 2: Geometric layout of the experimental field with a diagram showing the position of the static and dynamic load tests.

Fig. 2 also shows the method of implementation (position of individual test points) of the experimental measurements (static and dynamic load tests). Their number provides a sufficient set for a relevant statistical evaluation of the measured results. The structural and material layout of the experimental field under test is shown in Fig. 3.

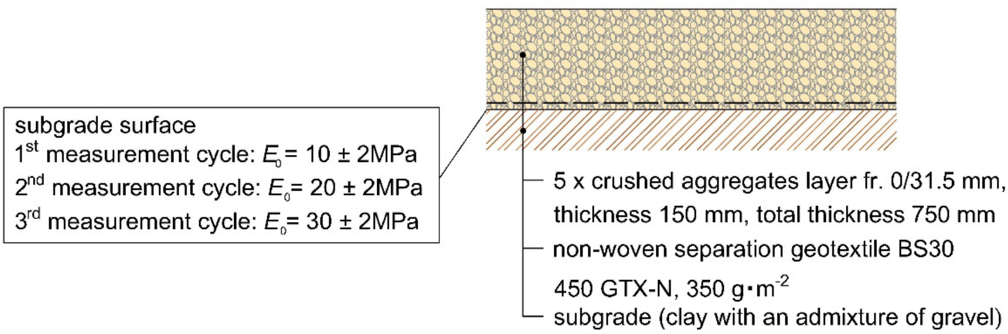

Fig. 3: The structural and material layout of the experimental field – cross-section A-A´.

Based on the granulometric test and grain-size curve, the subgrade of the experimental field was categorised as gravelly clay, with basic characteristics shown in Table 1.

Table 1: Basic characteristics of the experimental field's subgrade (gravelly clay).

w [%]	***ρ*** [kg·m^{-3}]	***w$_L$*** [%]	***w$_P$*** [%]	***C$_c$*** [-]	***C$_u$*** [-]	***I$_p$*** [-]	***I$_c$*** [-]
16.3	2114	39.0	18.8	0.14	114.98	20.2	1.12

Sampling for the evaluation of the subgrade's basic characteristics was carried out by a roller test (Fig. 4). The determined parameters were the material moisture content w, bulk density of the wet material ρ, soil moisture on the liquid limit w_L, soil moisture on the plasticity limit w_P, the number of curvature C_c, the number of the inequality of the grain size C_u, the soil plasticity index I_p and the soil consistency level I_c. The sampling and evaluation of the subgrade's basic characteristics were carried out in collaboration with the Department of Geotechnics, whose research activities are often focused on monitoring the parameters of fine-grained soils [28], [29]. During the experimental measurements, the deformation resistance of the subgrade (the value of static modulus of deformation at subgrade surface level) was considered in the way shown in Fig. 3. Thus, three measuring sessions with different deformation resistance of the subgrade were carried out.

Fig. 4: Sampling to evaluate the basic characteristics of the subgrade.

Subsequently, a non-woven separating geotextile fabric was placed on the top of the surface and the individual (partial) structural layers of crushed aggregate fr. 0/31.5 mm (dolomitic aggregate) from a quarry located circa 25 km from the university campus (Quarry in the Veľká Čierna – Fig. 5). The material forming the sub-ballast layer was imported directly from the quarry's stone breaker, to ensure a sufficient grain-size curve of the sub-ballast layer material. The overall thickness of the crushed aggregate structural layer was 750 mm. It consisted of 5 partial structural layers 150 mm thick. These partial layers were implemented to monitor the effect of the thickness of said structural layer on the increase of the static and dynamic deformation modulus. Based on the conducted pit test, the fraction of the crushed aggregate was 0/31.5 mm, the material moisture content w reached 2.6 % and the bulk density of the material ρ was 2176 kg·m^{-3}.

Fig. 5: Sorting and loading of the crushed aggregate fr. 0/31.5 mm in the quarry.

The experimental measurements saw 180 static load tests, following the test procedure DB A.G. (3 measuring sessions, 6 levels of measurement, 10 tests in one level of the structural layer), 180 static load tests following the ŽSR test procedure and 300 dynamic load test (these tests were not implemented on the subgrade surface of fine-grained soils, since the legislative document [30] does not recommend performing a dynamic load test on such a material). The diagram showing the method of implementation of static and dynamic load tests on the surface of a singular structural layer of the experimental field is evident in Fig. 2.

2.1 Determination of the Static Modulus of Deformation

Both test procedures to determine the static modulus of deformation (ŽSR TS 4 methodology [26] as well as DB A.G methodology [27]) are based on Boussinesq's solution of elastic half-space [2]. Within a given system with certain assumptions and model conditions applied, it is possible to calculate the stress course σ_r in the subgrade, according to the relation:

$$\sigma_r = A \cdot \frac{\cos\beta}{R^2}, \tag{1}$$

where *A* is a constant which can be determined by the equilibrium condition of the sum of the vertical components of the radial stress $\sigma_r \cdot \cos\beta$ over the surface of a hemisphere with a radius *R* and an acting force *P*.

By inserting the individual parameters followed by subsequent adjustments, it is possible to formulate the equation to calculate the subsidence of a rigid circular plate *y* (m), depending on the uniform pressure *p* ($N \cdot m^{-2}$) applied:

$$y = f \cdot \frac{p \cdot r}{E} \cdot (1 - \nu^2), \tag{2}$$

Equation (2) presents soil material's modulus of elasticity *E* (Pa), the radius of the load plate *r* (m), nondimensional stress distribution factor *f* a nondimensional Poisson's ratio *v* for soil material.

When dealing with the test procedures in question, the first difference in the determination of the static modulus of deformation occurs in the value of the substituted stress distribution factor. In the case of the DB A.G. test procedure, uniform stress distribution and value factor *f* = 2 are considered. On the other hand, the ŽSR test procedure considers load distributed through a rigid plate and the value factor is $f = \pi/2$ [31].

After substituting into equation (2) and defining the boundary conditions arising from the test procedure for determining the static modulus of deformation, the final equation (3), valid for the DB A.G. test procedure is obtained (a detailed derivation of the equation is provided in Appendix B of the Standard [27] and of the final equation (4) valid for ŽSR test procedure in [26]:

$$E_{def} = 1.5 \cdot r \cdot \frac{1}{a_1 + a_2 \cdot \sigma_{0,max}}, \tag{3}$$

$$E_{def} = 1.5 \cdot \frac{p \cdot r}{y}, \tag{4}$$

In equation (3), the value of the maximal stress impacting the load plate $\sigma_{0,\ max}$ ($MN \cdot m^{-2}$) operates with the first loading cycle of the static load test, since a lower value has been applied in the second loading cycle. Parameters a_1 ($mm/(MN \cdot m^{-2})$) and a_2 ($mm/(MN^2 \cdot m^{-4})$) can be calculated by solving the normal equations (see Appendix B in [30]) derived from equation:

$$y = a_0 + a_1 \cdot \sigma_0 + a_2 \cdot \sigma_0^2, \tag{5}$$

Static load tests can be carried out within both test procedures with the same set, consisting of the rigid circular plate with a 300 mm diameter, a beam with a lever extension arm, a hydraulic rig and a deformation (path) sensor. Fig. 6 (left) shows the static load set used during the measurements taking place on the experimental field (Fig. 3 and Fig. 6 on the right), consisting of a hydraulic rig FRÖWAG, accuracy of measurement 0.01 $MN \cdot m^{-2}$, range up to 0.8 $MN \cdot m^{-2}$ and digital deviation meter MITUTOYO with 0.01 mm accuracy of measurement and measuring range up to 25.4 mm.

Fig. 6: Static load tests conducted on the surface of the last partial structural layer of crushed aggregate fr. 0/31.5 mm.

Within both test procedures, the static load test is implemented in two loading cycles with the following main differences:

1) In the case of the ŽSR test procedure, the maximum stress $\sigma_{0,\, max}$ impacting the circular load plate was $\sigma_{0,\, max}$ = 0.2 MN·m^{-2} (the measurements were conducted on the sub-ballast layers level). In the case of the DB A.G test procedure, the $\sigma_{0,\, max}$ was 0.5 MN·m^{-2} (the maximum stress applied can also be lower if a 5 mm subsidence of the measured layer is achieved earlier).

2) In the case of the ŽSR test procedure, the loading cycle is divided into 4 loading levels (0.05; 0.10; 0.15 a 0.20 MN·m^{-2}), whereas in the case of the DB A.G. test procedure, there are 6 loading levels (0.08; 0.16; 0.25; 0.33; 0.42 a 0.50 MN·m^{-2}).

3) When dealing with the ŽSR test procedure, the transition to another loading level is carried out after the stabilisation of the deformation of the measured structural layer (if the change in deformation in 1 minute does not exceed 0.02 mm). In the case of the DB A.G. test procedure, the transition is constant, always after a period of 2 minutes.

4) In the case of the ŽSR test procedure, the calculation of the static modulus of deformation is carried out by an equation (4), based on the determined settlement (drop) of the measured structural layer. When dealing with the DB A.G. test procedure, equation (3) was used, based on the determination of the a_1 and a_2 coefficients resulting from the trend equation of the drawn measurement curve.

2.2 Determination of the Dynamic Modulus of Deformation

The test procedure for the implementation of dynamic load tests is based on the static theory of impact [32]. In practice, however, further simplifications were installed, and the engineering theory of impact was applied. A necessary precondition to determine the dynamic modulus of deformation of the measured structural layer is the surface contact between the elastic half-space and a rigid cylinder – Fig. 7 left [33].

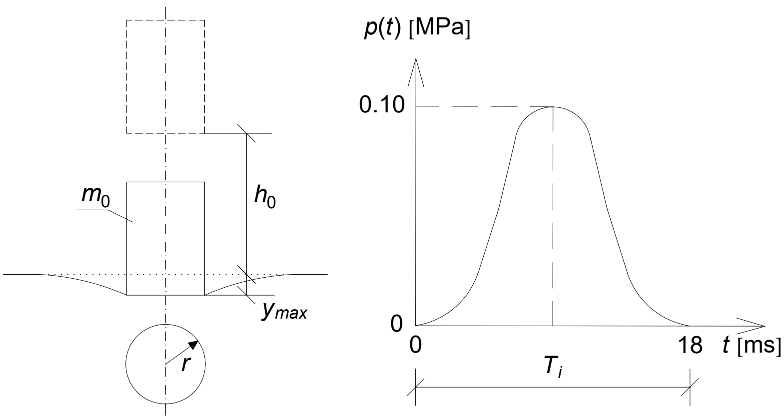

Fig. 7: Surface contact between the elastic half-space and a rigid cylinder (left), and the time limit of the dynamic load test (right).

For such a set with precisely specified boundary conditions, the following equations then apply:

$$P = \frac{2 \cdot a \cdot E_1}{1 - \vartheta^2} \cdot y = C_1 \cdot y, \quad (6)$$

$$-m_0 \cdot \frac{d^2 y(t)}{dt^2} - C_1 \cdot y(t) = 0, \quad (7)$$

After modification:

$$\frac{d^2 y(t)}{dt^2} + \omega_0^2 \cdot y(t) = 0, \quad (8)$$

$$\omega_0 = \sqrt{\frac{C_1}{m_0}}, \quad (9)$$

The time of impact can be subsequently represented by the relation:

$$t_r = \frac{T_0}{2} = \frac{\pi}{\omega_0} = \pi \sqrt{\frac{m_0}{C_1}}, \quad (10)$$

The maximal push velocity and maximal impact force can be calculated by equations:

$$v_{max} = \frac{c_0}{\omega_0} = \sqrt{\frac{m_0 \cdot g \cdot h_0 \cdot (1 - \vartheta^2)}{a \cdot E_1}}, \quad (11)$$

$$P_{max} = C_1 \cdot y_{max} = \sqrt{\frac{4 \cdot m_0 \cdot g \cdot h_0 \cdot a \cdot E_1}{1 - \vartheta^2}}, \quad (12)$$

In equations (6) to (12), the following parameters are used:
P - pressure force (N),
y - pushing force (N),
a - radius of the cylinder (m),
E_1 - the elasticity modulus of half-space material (MPa),
v - Poisson´s ratio (-),
m_0 - weight of the rigid body (kg),
ω_0 - angle frequency of movement (rad·s^{-1}),
c_0 - the velocity of the rigid body impact (m·s^{-1}),
h_0 - height of the fall of the rigid body (m),
g - acceleration of gravity (m·s^{-2}).

The final relation used to calculate the dynamic modulus of deformation stated in the instruction manual of the light weight deflectometer is:

$$E_{vd} = \frac{F}{d \cdot y_{e1}} \cdot (1 - \vartheta^2), \quad (13)$$

In equation (13), the input parameters are the maximum impact force *F* = 7070 ± 70 N, the diameter of the load plate *d* = 0.30 m, nondimensional Poisson number *v* and recorded deflection amplitude from the load plate axis y_{e1} (m). For the needs of ŽSR, the measuring procedure utilising impact load set on the sub-ballast layers is stated in the TS 4 Regulation [26] which follows the DB A.G. norm [30]. The principle of the dynamic load test is based on a short-term, precisely defined impact load of the rigid circular plate with r radius and recording subsidence (drop) below the centre of the subject plate y caused by a damped shock pulse of approximately half sine wave shape. Shock pulse is initiated by a weight falling from a specified height onto a circular load plate equipped with a shock absorber, which divides the action of force into a specific time limit *Ti* (Fig. 6 right). During the dynamic load test, a contact stress σ = 0.10 MPa is determined under the circular load plate, which approximately corresponds to the railway operation stress at the level of the sub-ballast upper surface. This contact stress induces tension in the measured structural layer along with its deformation (elastic or plastic). At the same time, the deflection in question is monitored by a suitable deviation (path) sensor. Fig. 8 shows the set for the dynamic load test, employed during experimental measurements, consisting of the guide rod (1), 10-kilogram weight (2), shock absorber (3), deflection sensor (4), circular load plate with radius *r* = 0.15 m (5) and a control and evaluation unit (6).

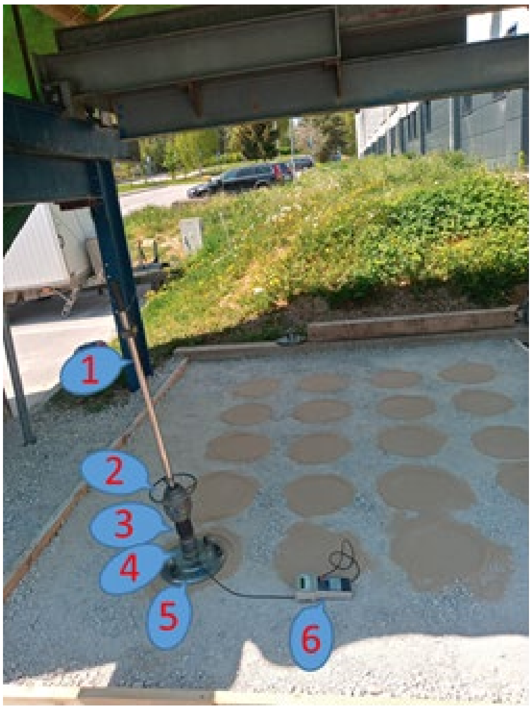

Fig. 8: Dynamic load test set and locations of the experimental stand.

3 Results Achieved and Discussion

Determination of the correlation dependence between the deformation resistance values of the tested material concluded by the static and dynamic load test is difficult, as it depends on several measurement boundary conditions (characteristics of the tested building material, its moisture and compaction, the thickness of the measured structural layer or, in the case of a low thickness of the measured layer, the properties of the subgrade. The correlation dependence can be determined only with a sufficient number of gained results for specific, "invariable" boundary conditions. During the experimental measurements, this was ensured by testing an identical material and by the fact, that the thickness of the tested structural layer stayed the same. Experimental measurements and subsequent determination of the correlation dependence in question were conducted for a widely-used building material (crushed aggregate), used in the sub-ballast layer of the railway line. More detailed boundary conditions of the experimental measurements (material specifications, their diagram and methodology, number of measurements taken) are specified in Chapter 2.

3.1 The Correlation Dependence Between the Static Modulus of Deformation Values Determined by the Test Procedures in Question

Fig. 9 and 10 show the correlation dependence between the static and dynamic modulus of deformation determined by all experimental measurements carried out (150 static load tests for the ŽSR test procedure, 150 for the DB A.G. test procedure and 300 dynamic tests using LDD 100). It is necessary to point out that the figures show the measurement results from all three measuring sessions, with the 1st one being characterised by deformation resistance of the subgrade surface E_0 = 10 ± 2 MPa, the 2nd by deformation resistance of the subgrade surface E_0 = 20 ± 2 MPa and the 3rd one by deformation resistance of the subgrade surface E_0 = 30 ± 2 MPa.

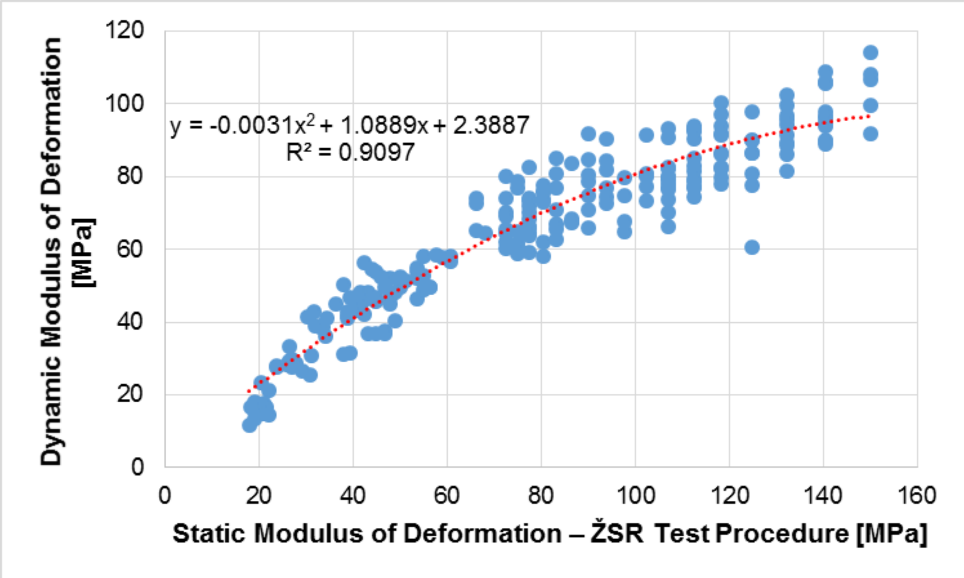

Fig. 9: The dependence determined between the static modulus of deformation (set by ŽSR test procedure) and dynamic modulus of deformation (set by LDD 100 method) for the sub-ballast layer of crushed aggregate fr. 0/31.5 mm of different structural thickness.

Fig. 9 as well as Fig. 10 show, that even despite sufficient correlation dependence, the measured values, especially in the case of higher determined deformation resistance of the measured layer, have significant dispersion (in most instances, the dispersion of the measured values on the structural layer surface ranged from 10 to 25 MPa, although in some cases, it exceeded 40 MPa). Therefore, it was decided to proceed to the statistical evaluation of the measured values. It is necessary to point out, that during static load tests, carried out by DB A.G. test procedure [27], the maximum value of normal stress acting below the load plate 0.5 $MN \cdot m^{-2}$ for partial crushed aggregate layers with thickness 150 mm and 300 mm was not applied (instead, the value of the normal stress obtained when the load plate subsidence value approached 5 mm was used).

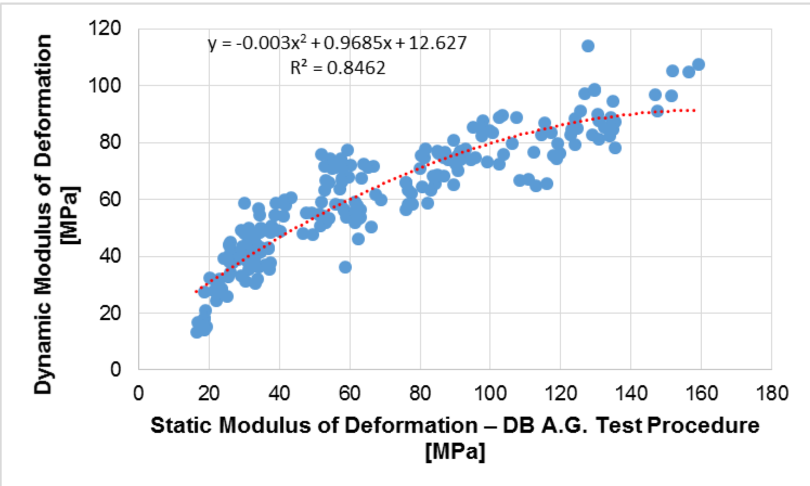

Fig. 10: The dependence determined between the static modulus of deformation (set by DB A.G. test procedure) and dynamic modulus of deformation (set by LDD 100 method) for the sub-ballast layer of crushed aggregate fr. 0/31,5 mm of different structural thickness.

Using the values of the deformation resistance determined at the surface of the partial structural layers of crushed aggregate fr. 0/31.5 mm, the value of the arithmetic mean according to the relation was first established.

$$\overline{E_{def}} = \frac{1}{N} \cdot \sum_{i=1}^{N} E_{def,i} \, , \quad (14)$$

The standard deviation was then calculated for the individual measured deformation resistance values:

$$\sigma = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (E_{def,i} - \overline{E_{def}})^2}, \quad (15)$$

Values out of range were subsequently excluded from the data set:

$$\left(\overline{E_{def}} - 2\sigma; \overline{E_{def}} + 2\sigma\right), \quad (16)$$

After excluding the incorrect values, the arithmetic mean of the deformation resistance for partial structural layers of crushed aggregate was calculated and a graphical dependence representation encompassing the measured and subsequently corrected set of these values was constructed — Fig. 11 and 12.

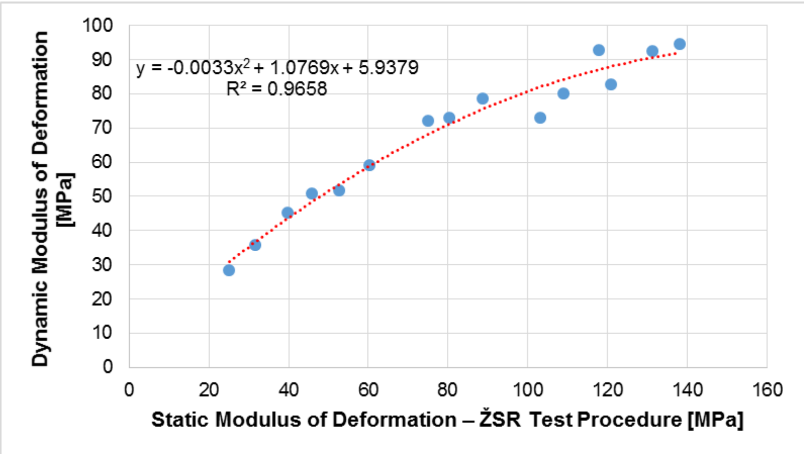

Fig. 11: The dependence determined between the static module of deformation (set by ŽSR test procedure) and dynamic module of deformation (set by LDD 100 method) for the sub-ballast layer of crushed gravel fr. 0/31.5 mm of different structural thickness – after the statistical evaluation.

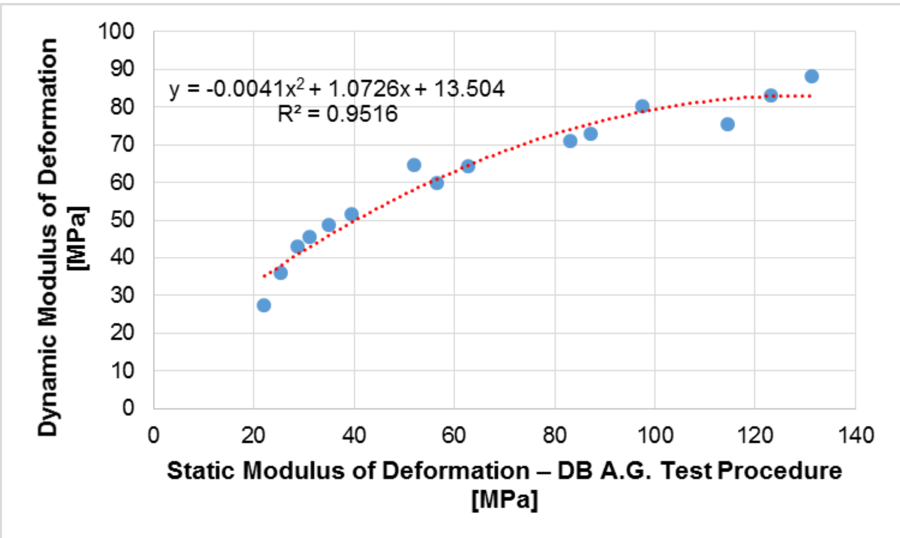

Fig. 12: The dependence determined between the static modulus of deformation (set by DB A.G. test procedure) and dynamic modulus of deformation (set by LDD 100 method) for the sub-ballast layer of crushed aggregate fr. 0/31.5 mm of different structural thickness – after the statistical evaluation.

Figures 11 and 12 show that after statistically excluding the incorrect measurement values and constructing a correlation dependence from the deformation resistance values obtained via the arithmetic mean for the individual partial crushed aggregate layers, it is possible to obtain a very high accuracy of the coefficient of determination (R^2 > 95 %).

Since the experimental measurements were conducted in several measuring sessions (monitoring the impact of different deformation resistance of the subgrade surface) and on the surface of partial structural layers of crushed aggregate fr. 0/31.5 mm of various structural thicknesses, the influence of these boundary conditions of measurement on the obtained value of the dynamic modulus of deformation is shown in Fig. 13 and 14. The influence of the subgrade surface's deformation resistance is depicted by multi-coloured curves, where the blue curve represents the lowest deformation resistance of the subgrade surface considered during experimental measurements (E_0 = ca. 10 MPa), and the grey curve represents the highest deformation resistance of the subgrade surface (E_0 = ca. 30 MPa).

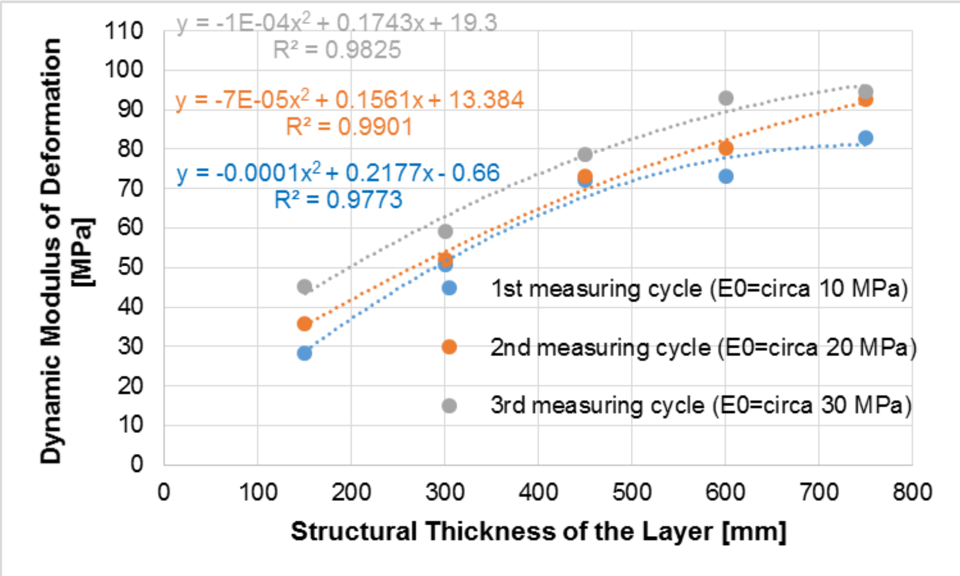

Fig. 13: The dependency of the dynamic modulus of deformation on the structural thickness of the partial layers of crushed aggregate fr. 0/31.5 mm and deformation resistance on the subgrade surface level (values gained by comparison with static load test performed under ŽSR test procedure).

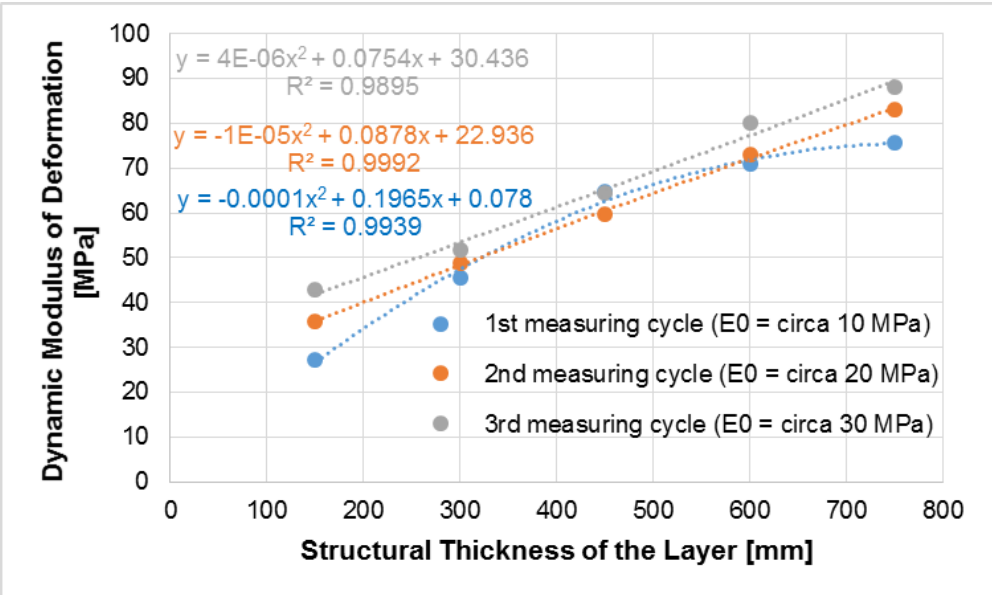

Fig. 14: The dependency of the dynamic modulus of deformation on the structural thickness of the partial layers of crushed aggregate fr. 0/31.5 mm and deformation resistance on the subgrade surface level (values gained by comparison with static load test performed under DB A.G. test procedure).

Figures 13 and 14 show that despite the noticeably high value of the coefficient of determination R^2, it is challenging to monitor the effect of any of the boundary conditions on the increase in the value of dynamic modulus of deformation, since, as mentioned before, this value is dependent on numerous initial conditions (moisture of the measured structural layer, its compaction, material composition, etc.). Therefore, it is highly difficult, if not impossible, to re-create them equally in all conducted measurements, although they were carried out in the "optimal" conditions for the construction of the tested structure.

4 Conclusion

Based on the literature review and executed series of experimental measurements conducted to determine the correlation between static and dynamic modulus of deformation, the following conclusions can be formulated:

1) The theoretical basis of the static load tests performed by the ŽSR, or DB A.G. test procedure lies in Boussinesq's solution of elastic half-space, whereas the basis of dynamic load tests performed by using light weight deflectometer LDD 100 in the engineering theory of impact. Among the main differences in test procedures of the executed static and dynamic load tests (described in detail in part 2.1) fall different maximum contact values of the normal stress under the load plate (0.1 MPa; 0.2 MPa, or 0.5 MPa), different ways of recording the subsidence of the plate (based on the impact effects of weights, regular 120 second time step and monitoring the stabilisation of the plate subsidence) and different relations for the calculation (relations (3), (4) and (13)).

2) When ensuring approximately equal boundary conditions (roughly the same deformation resistance of the subgrade, same material applied to the structural layer of crushed aggregate, same compaction method), it is possible to achieve high value of coefficient of determination between the values of static and dynamic modulus of deformation (R^2 > 84 % in the case of static tests conducted by using DB A.G. test procedure – Fig. 10 or R^2 > 90 % in the case of static tests conducted by using ŽSR test procedure – Fig. 9). When performing a sufficient set of measurements, their statistical evaluation and exclusion of incorrect measurements, coefficient of determination R^2 > 95 % can be achieved (Fig. 11 and 12). The suggested dependence is valid for building materials nowadays frequently used in the construction of sub-ballast structural layers – crushed aggregate, specifically fr. 0/31.5 mm made from crushed dolomitic rock. Its validity needs to be verified also for another rock material of the sub-ballast layer as well as other fractions (0/45 mm or 0/63 mm).

3) The dispersion between the lowest and the highest measured value of the static modulus of deformation, determined on the surface of the partial structural layers of crushed aggregate, proved more favourable for values determined by the DB A.G test procedure (dispersion of values up to 17 MPa). In comparison, the ŽSR test procedure recorded the dispersion of values from 5 to 25 MPa. When regarding the dynamic modulus of deformation, the determined dispersion of values was from 10 to 27 MPa, even 45 MPa one time (to validate this result, the test was repeated several times – nevertheless, the value remained the same). Thus, it can be concluded that after a sufficient number of measurements and the exclusion of incorrect values, satisfactory reliability of the measurement results can be achieved.

4) The dependency of the dynamic modulus of deformation on the structural thickness of the layer of crushed aggregate fr. 0/31.5 mm and various deformation resistance of the subgrade (Fig. 13 and 14) are characterised by high values of coefficient of determination R^2 > 97 %. However, based on the course of the curves (mathematical dependencies), it is clear that other measurement conditions (present moisture content of the partial structural layer of crushed aggregate, compaction rate) also influenced the obtained dependency.

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