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RELATIONSHIP BETWEEN DEFORMATION MODULI OBTAINED USING LIGHT FALLING WEIGHT DEFLECTOMETER AND STATIC PLATE TEST ON VARIOUS TYPES OF SOIL

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Abstract. There is increasing effort to optimize test methods for evaluation of subgrade. It takes effect in aspiration in replacement of static plate loading test by other faster test methods. One of them is the use of Light Falling Weight Deflectometer. In many countries in Europe both static and dynamic plate tests are standardized. The presented paper introduces results of the research project dealing with the sensitivity of the relationship between static modulus and modulus obtained from the Light Falling Weight Deflectometer on specific types of soil. It is shown that there are significant differences in relationship between moduli values obtained using both methods on different types of soil.

Keywords: deformation moduli, soil moduli, Falling Weight Deflectometer (FWD), Light Falling Weight Deflectometer (LFWD), static plate tests, moduli relationship.

1. Introduction

In many countries in Europe there is a static plate loading test one of the tests required for a quality assessment of earthworks. Elastic or deformation modulus is an output of the test and there are limitations stated by standards necessitating achievement of minimum value of the modulus, e.g. in Germany and in Austria the standards *DIN 18 134:1990 Baugrund; Versuche und Versuchsgeräte; Plattendruckversuch* [Subsoil; Testing and Equipment; Plate Loading Test] and *ONORM B 4417:1979 Erd- und Grundbau; Untersuchung von Böden; Lastplattenversuch* [Geotechnical Engineering (Foundation Engineering); Soil Investigation; Plate Loading Test] respectively both describe measurement of deformation modulus obtained from the second loading cycle (next chapter for explanation) as well as the standard *CSN 72 1006:1998 Kontrola zhutneni zemin a sypanin* [Verification of Compaction of Soils and Loose Materials] in the Czech Republic. The minimum value for road subgrade is defined as 45 MPa. The Czech standard *TP 170:2004 Navrhovani vozovek pozemnich komunikaci* [Road Pavement Design] divides subgrade into three types, the first one has a minimal value of deformation modulus 90 MPa, the second one 60 MPa and the third one 45 MPa. Similar situation is in Austria, Slovakia, Switzerland and other countries.

Visibly, deformation modulus measured using the static plate test in the second loading cycle is a routine test done many times at each construction place. The test, including preparation, takes at least half an hour and needs a lorry for its execution usually. This implicates strong effort to replace the static plate test by a faster test as the dynamic plate test, which uses one-man apparatus, i.e. the Light Falling Weight Deflectometer (LFWD).

A central hypothesis of the presented research is expressed as follows: Relationship between static and LFWD deformation moduli is affected by a type of tested soil.

Findings of the research are useful for predicative ability to use LFWD instead of static plate test in countries where static test is one of mandatory tests having to be done for the acceptance of earth works quality. In countries where the static plate test is not stated as a primary test for quality assessment (QA) of earthworks the LFWD tests are deeply influenced by soil type and they do not represent elastic-plastic soil behaviour apart from the fact that the value of elastic modulus obtained from LFWD strongly correlates with used equipment (Vennapusa, White 2009).

2. Static plate loading test

As mentioned in the previous chapter the static plate loading test resulting in the value of deformation modulus obtained from the second loading cycle is one of the essential tests which should be done on subgrade before laying pavement layers.

The test according to already cited German standard *DIN 18 134:1990* as well as the Czech standard

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CSN 72 1006:1998 and similar others in Austria, Slovakia and Switzerland is done using 300 mm diameter plate which is placed on subgrade to be tested. Loading is realized by a hydraulic facility propped against a lorry usually. A deformation relating to load is measured using lever system and often recorded automatically to a computer (Fig. 1).

The test consists of two loading cycles with one unloading cycle between them. After pre-loading the first loading cycle starts. It consists of at least seven linearly increasing loading steps. In each loading step a constant tension is kept for 120 s and after that deformation is recorded, keep track of Fig. 2, where load and relating deformation are displayed. The last step of the cycle, i.e. the maximum loading, is defined by prescribed maximum loading or deformation.

The test continues with unloading cycle in three steps. The first unloading step is in the half of maximum loading, the second step in its quarter and the third one quite unloaded. Just after 120 s period on the third unloading step the second loading cycle starts similarly as the first loading cycle. Its last step is on the level of the last but one step of the first loading cycle. The test process is shown in Fig. 2 displaying the first loading cycle, unloading and the second loading cycle.

Fig. 1. Static plate loading test

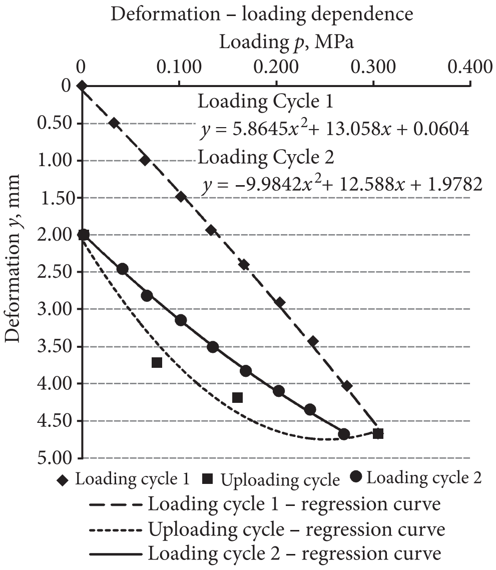

Fig. 2. Record of the static plate loading test

The deformation modulus is defined using Eq (1):

$$E_{def} = \frac{1.5\Delta pr}{\Delta y}, \text{ MPa}, \tag{1}$$

where E_{def} – static deformation modulus in the specific loading cycle, MPa; Δp – maximum loading or change of stress under plate, MPa; r – radius of loading plate (usually 0.15 m), m; Δy – maximum deformation or change of vertical strain in centre of plate, mm.

According *DIN 18 134:1990* the formula shown in Eq (1) has to be modified using regression curve as a function of load values on a specific loading step, Eq (2):

$$y = a_0 + a_1 p + a_2 p^2, \text{ m}, \tag{2}$$

where y – vertical plate displacement as a function of specific loading; p – specific loading, MPa; a_0, a_1, a_2 constants of regression polynomial.

Constants of regression polynomial introduced in Eq (2) are expressed using method of least squares shown in Eq (3):

$$\begin{bmatrix} n & \sum p_i & \sum p_i^2 \\ \sum p_i & \sum p_i^2 & \sum p_i^3 \\ \sum p_i^2 & \sum p_i^3 & \sum p_i^4 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \sum y_i \\ \sum p\ y_i \\ \sum p_i^2 y_i \end{bmatrix}, \tag{3}$$

where n – number of loading steps in the specific loading cycle.

Taking the change of loading Δp as a difference between specific loading p_1 and p_2 and change of displacement Δy as a difference of corresponding displacements y_1 and y_2 , it results in rewriting of Eq (1) in the shape of Eq (4):

$$E_{def} = 1.5r\frac{p_1 - p_2}{y_1 - y_2}, \text{ MPa}. \tag{4}$$

Inserting Eq (2) to Eq (4) the Eq (5) is obtained:

$$\begin{gathered} E_{def} = 1.5r\frac{p_1 - p_2}{a_0 + a_1 p_1 + a_2 p_1^2 - a_0 - a_1 p_2 - a_2 p_2^2}, \text{ MPa}; \\ E_{def} = 1.5r\frac{1}{a_1 + a_2(p_1 + p_2)}, \text{ MPa}. \end{gathered} \tag{5}$$

Using the presumption of *DIN 18 134:1990* that modulus of deformation should be expressed in range of definition of loading p_1 and p_2 defined by Eq (6):

$$p_1 = 0.3p_{\max}, \text{ MPa}; \; p_2 = 0.7p_{\max}, \text{ MPa}. \tag{6}$$

where $p_{\max}$ – maximum loading in the specific loading cycle. Expression of loadings p_1 and p_2 defined in Eq (6) as a $p_{\max}$ loading functional relation permits to rewrite Eq (5) to the form of Eq (7), which is the formula for deformation modulus according *DIN 18 134:1990:*

$$E_{def} = \frac{1.5r}{a_1 + a_2 p_{\max}}, \text{ MPa}. \quad (7)$$

As the deformation modulus is understood as a quality assessment test, its prospective value in the time of designing is useful to know. For this reason there are some research works comparing the type of modulus with California Bearing Ratio (CBR) (Floss 1973; Pospisil 2005).

3. Dynamic plate test by Light Falling Weight Deflectometer

In the previously mentioned European countries the dynamic plate test done by LFWD is carried out according to the German standard *TP-BF StB:2003 Technische Prüfvorschriften für Boden und Fels im Sraßenbau, Teil B 8.3: Dynamischer Plattendruckversuch mit Leichtem Fallgewichtsgerät* [Technical Guideline for Soil and Rock Testing, Vol. B 8.3: Dynamic Plate Test Using Light Falling Weight Deflectometer] and its national clones, such as the Czech standard *CSN 73 6192:1996 Razove zatezovaci zkousky vozovek a podlozi* [Pavement and Subsoil Dynamic Loading Tests]. The main components of the device are a load plate, similar as in case of the static plate test, a guide-rod, a steel spring or a synthetic damper and a falling weight (Fig. 3). The guide-rod is loosely coupled with the plate within a small ball. A sensor mounted in the midpoint of the load plate registers the acceleration.

During the field test, the falling weight is released and it slides down along the guide-rod until it strikes the damper element. Since the rod rests loosely on the small ball joint only, compression forces are transferred to the load plate, which is positioned horizontally on the tested subgrade. Before testing, three preload impacts are conducted in order to ensure full contact between the load plate and the soil. The test is conducted three times and the average value of three vertical peak displacements of the plate is taken as an input value to the modulus calculation using Eq (8), which is formally similar to Eq (1).

$$M_{vd} = 1.5\frac{rp}{y}, \text{ MPa}. \quad (8)$$

where M_{vd} – dynamic deformation modulus, MPa; r – plate radius (usually 0.15 m), m; p – maximum loading, MPa; y – maximum deformation (deflection), mm.

Test results are usually recorded and evaluated by an electronic unit connected to the LFWD device. In comparison with the static plate loading test the use of LFWD takes about one tenth of time.

4. Theoretical starting points

There are many equipment types called light falling weight deflectometers on the market useful for dynamic modulus measurement. According to Vennapusa and White (2009) and Tompai (2008), they vary in measured values of dynamic subgrade modulus. However, the task of the paper is not to compare these equipment and difference among them is not discussed, it is supposed that differences between dynamic and static moduli are characteristic of different principles of their measurement methods. In-depth theoretical analysis of ground–structure interaction in a dynamic plate load testing done using rather a regular FWD is shown e.g. in Guzina and Fata (2002).

As shown by Adam *et al.* (2009) (Fig. 5), static test affects subgrade deeper than LFWD but not significantly. It seems that distribution of deformation is more considerable difference between both tests. While distribution of deformation in case of the static test is consumed approximately up to 0.3 m of subgrade depth, in case of LFWD test the same ratio of deformation is observed roughly at a depth of 0.5 m, compare left and right side of Fig. 5.

The main interest of (Adam *et al.* 2009) from this paper point of view has been found in extensive numerical parametric studies of the static and the dynamic load plate tests conducted in order to evaluate the effect of layered earth structures of different stiffness on the test results. It was observed that for an ideal homogeneous soil medium the dynamic deformation modulus is larger than the static one. With increasing layer of thickness the difference between both moduli becomes more pronounced. For soil stiffer than the underlying half-space, dynamic modulus is larger than static modulus for all layer

Fig. 3. Dynamic plate loading test using LFWD

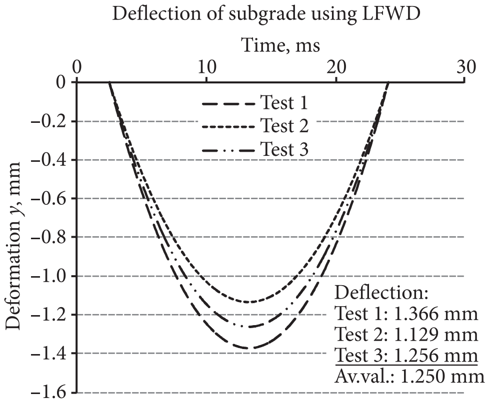

Fig. 4. Record of LFWD test

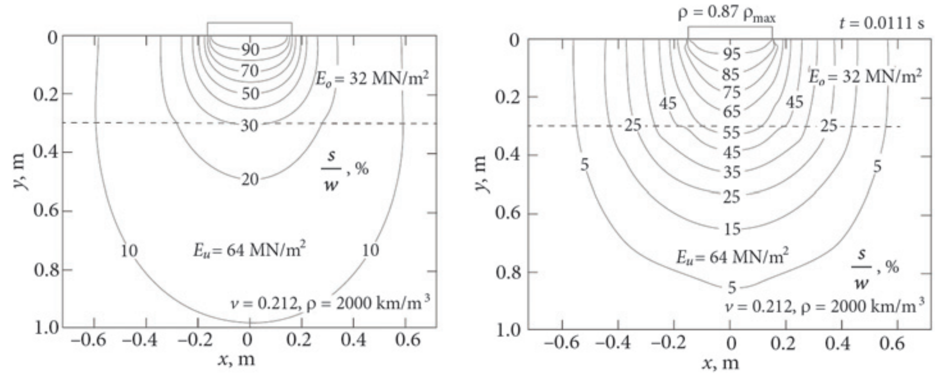

Fig. 5. Comparison of static (left) and dynamic (right) tests range (Adam *et al.* 2009)

thicknesses. In contrast to it, when modulus of elasticity of soil layer is smaller than elastic modulus of half-space the dynamic deformation modulus is larger than static deformation modulus only for thin layers. With increasing soil layer thickness, the difference becomes smaller and finally, the static load plate test renders a larger deformation modulus than the dynamic load plate test. It corresponds with the different engagement depth of both plate test types.

Asli *et al.* (2012) show the back-calculation procedure of homogenous elastic modulus from data obtained from LFWD. They highlighted questions about the reliability and accuracy of the peak value method commonly used to extract the static stiffness of soils and subgrade from the dynamic transient data. Their research is based on data analysis and identification of soil elastic stiffness.

Ahmed and Khalid (2011) present an experimental and modelling study of the elastic dynamic response of a foundation layer of Incinerator Bottom Ash (IBA) waste and limestone that was subjected to LFWD impact loading. Several parameters such as IBA content, water content, and curing time were studied. Regression, mathematical, and three-dimensional finite element models were developed to back-calculate the LFWD moduli of the foundation layers. The modelling approach accounted for the static and impact nature of the LFWD load. Back-calculated modulus results based on the dynamic effect of the LFWD load produced different values from those calculated by Boussinesq's equation, which is adopted by the LFWD manufacturer.

Liu *et al.* (2006) showed seven clay samples with different water content the relationship between dynamic and static elastic moduli and demonstrated water content and density as a variation to study dynamic, static elastic parameters. Mashinsky (2003) dealing with moduli of rocks describes differences between measured static and dynamic elastic moduli. They are caused by different inelastic contributions to stress-strain relationships which change as a function of strain amplitude and frequency (energy and strain rate). He states that static and dynamic elastic moduli can be appropriately compared at equal strain amplitudes and frequencies and at identical physical properties of solids.

Alshibli *et al.* (2005) deal with assessment of the potential use of the geo-gauge and LFWD as quality control/quality assurance devices for testing subgrades, base courses, and compacted soil layers. A comprehensive laboratory experimental program was conducted on compacted layers of silty clay, clayey silt, cement-treated clay, sand, gravel, recycled asphalt pavement, and limestone aggregates. The geo-gauge, LFWD, static plate load test, and the dynamic cone penetration (DCP) measurements were acquired for the constructed layers. The geo-gauge elastic modulus and the LFWD dynamic modulus were correlated with the static plate test. The results of this study show that the geo-gauge and the LFWD are used to calculate the elastic modulus/stiffness characteristics of compacted layers. Whereas the geo-gauge and the LFWD determined the initial modulus of the cement-treated clay, they did not yield accurate measurements of strength gain with time. Good statistical correlations were found between elastic moduli measured by the devices used in this investigation. Vennapusa *et al.* (2012) present similar tests comparing in situ point test measurements using falling weight deflectometer (FWD), light weight deflectometer (LFWD), dynamic cone penetrometer and static piezocone, and near continuous roller-integrated continuous compaction control measurements on a granular pavement foundation embankment. They discuss limitation of used equipment.

There are several other research studies correlating geotechnical evaluating tests, i.e., Lacey *et al.* (2013) correlate DCP and LFWD tests, Ji *et al.* (2014) correlate laboratory resilient modulus, Vennapusa *et al.* (2013) correlate roller compaction control value (CCV) and FWD modulus, Muller and Roberts (2013) compare a traffic speed deflectometer (TSD) with FWD, Salour and Erlingsson (2013) observe relation between measured subsurface moisture content and FWD moduli, Oh *et al.* (2012) correlate laboratory and field obtained moduli etc. On the other hand several studies use LFWD as a tool for different kind of analyses: Benedetto *et al.* (2012, 2014), Sulewska (2012), Khattak *et al.* (2012) and Shin (2012a, 2012b).

5. Presumptions, aim and hypothesis of the research

The presented research takes into account the published research works. For prevention of stratified subsoil layer influence the tests were done on a homogenous at least 1.2 m thick layer, compare with Fig. 5 taken from Adam *et al.* (2009). Arrangement of experiments respects the findings of Vennapusa and White (2009) that a value of dynamic moduli is strongly related with the type of LFWD equipment. LFWDs used for experiments were of the same type. Static and dynamic tests were done in the same time on the same place. On that account the presumption of Liu *et al.* (2006) concerning equal moisture content was kept. The research was followed up by Alshibli *et al.* (2005) but he used European standards for the static plate test determination and relativizes their findings concerning "good statistical correlations between elastic and LFWD moduli".

Relationship of static and dynamic moduli stated using Eqs (7) and (8) has been expressed as their ratio, Eq (9).

$$P_1 = \frac{E_{def,1}}{M_{vd}};\; P_2 = \frac{E_{def,2}}{M_{vd}}, \qquad (9)$$

where P_1 – ratio of static modulus of deformation calculated from the first loading cycle $E_{def,1}$ and dynamic LFWD modulus M_{vd}; P_2 – ratio of static modulus of deformation calculated from the second loading cycle $E_{def,2}$ and dynamic LFWD modulus M_{vd}.

Poisson's ratio as a soil characteristic has not been determined because according to the cited standards formulas for moduli calculation, Eqs (7) and (8) do not include the Poisson's ratio of tested soil. They consider Poisson's ratio as a constant with value 0.2. Indeed, this fact makes moduli calculation inaccurate for soils with different Poisson's ratio, but for the purpose of the presented research this inaccurateness has no influence. As both static and dynamic moduli expressed with their "full-formulas" at Eq (10) includes Poisson's ratio in brackets (1 – ν), which multiple other parts of formulas, and the ratio between static and dynamic moduli has been being found, the brackets containing Poisson's ratio are reduced. This approach eliminates any influence of Poisson's ratio.

$$E_{def} = \frac{\pi}{2}\left(1-\nu^2\right)\frac{\Delta pr}{\Delta y},\ \text{MPa};\ M_{vd} = \frac{\pi}{2}\left(1-\nu^2\right)\frac{rp}{y},\ \text{MPa}, \qquad (10)$$

where ν – the Poisson's ratio of tested soil and other symbols are defined in the legends to Eqs (1) and (8). Note: if it is taken that $\nu = 0.2$ and $\pi = 3.14$, Eqs (1), (7) and (8) will be obtained.

Aim of the research was to verify the hypothesis that ratio between static and dynamic moduli differs from soil to soil. Aim of research was not to find out "a universal" ratio for each possible kind of soil because it stands to reason that the relationship between moduli is more delicate matter than the kind of soil only.

6. Experiment arrangement

As indicated in the Introduction part, the research was concerned with hypothesis, that relationship between the static and LFWD deformation moduli is affected by a type of tested soil. Experiments were arranged as both laboratory and field tests. Laboratory tests were done in the Geotechnical Laboratory Testing Field (GLTF), which is a research facility of Transport Research Centre (CDV). The GLTF allows measurement of some of the geotechnical quantities, which are usually measured in the field, i.e. the static plate test, the dynamic test, the penetration test, etc., on various soils and soil layers for different compaction rate and water regimes. The GLTF is equipped by a dynamic/cyclic loader for the traffic loading simulation (this feature was not exploited in the research). Therefore the GLTF is able to be used as an Accelerated Pavement Tester as well. Fig. 6 displays GLTF schematic view and Fig. 7 shows measurement of static plate and LFWD tests in the GLTF.

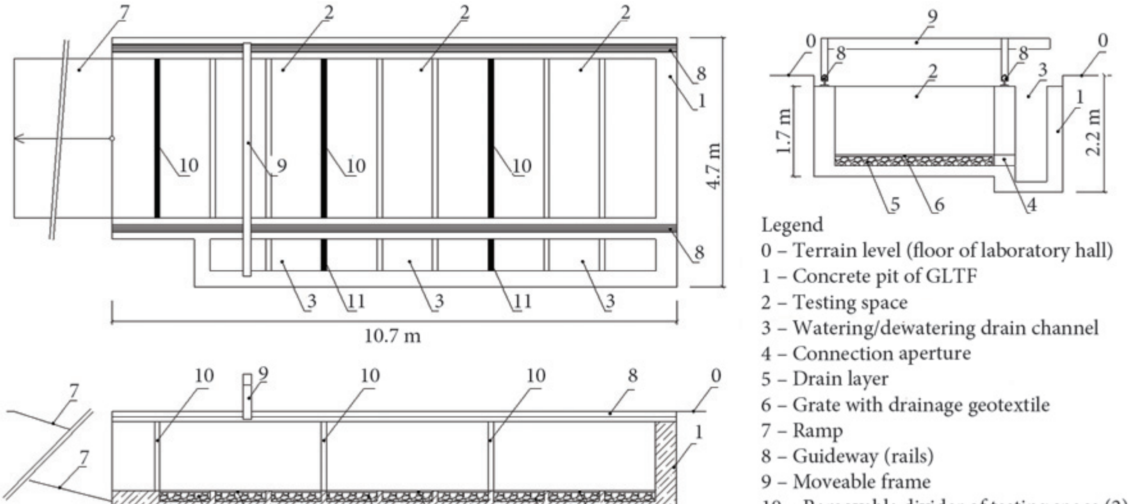

Fig. 6. GLTF built in laboratories of CDV (Pospisil 2005)

Laboratory and field tests were done in seven testing sets (Table 1).

As shown in Table 1 the first three test sets (No. 1–3) were done in the GLTF. Next four test sets (No. 4–7) were done in-situ within an inter-laboratory comparison testing (tests No. 4, No. 5, and No. 6) and within commercial testing (test No. 7).

7. Test results

Test results obtained from all 7 sets of tests are given in Table 2. In cases of the test sets No. 4–7, static and dynamic moduli values represent average values obtained in one section of prepared subgrade (note of Table 1). It means that the displayed values of moduli in case of field tests are more reliable than it is expected at first (Table 2).

8. Results discussion

However, the presented tests do not propose to state "a universal" ratio between static and dynamic tests for selected types of soils, they show how to vary the ratio between them soil to soil. If the research is not quantitative (number of tests and selected soil is not sufficient), the results taken from the qualitative point of view show that ratio between dynamic and static modulus strongly correlates with the used kind of soil. Table 3 declares the mentioned variability.

The summarised results at Table 3 show that the ratio between static and dynamic moduli more or less increases with a quality of soil and having in mind the size of statistical file the relationship between static and dynamic moduli does not have "good statistical correlations" as found by Alshibli *et al.* (2005). It means that if somebody likes to use dynamic modulus instead of static modulus, he/she will have to make similar correlation tests as presented and set very conservative level of reliability of found ratio between moduli. Fig. 8 shows possible expression of reliability level for each type of soil.

In case of Fig. 8 the reliability level was calculated from a cumulative function which ordered obtained ratios from "most proper" to "most improper", e.g. from quality assessment point of view, and e.g. reliability 60% means that 60% of obtained ratios is under (above) displayed value.

Fig. 7. Tests in the GLTF: static plate test (left) and dynamic LFWD test (right)

Table 1. Soil tested

Test set No.	Test place and arrangement	Number of averaged values*			Number of ratios P_1, $P2$	Soil tested
		$E_{def,1}$	$E_{def,2}$	M_{vd}		
1	GLTF		*N/A*		11	Clay with intermediate plasticity
2	GLTF				8	Sandy loam
3	GLTF				8	Gravel with fine soil impurity
4	Field test	3	3		14	Loam gravel
5	Field test	3	3		4	Loam gravel
6	Field test	3	3		9	Gravel well-graded
7	Field test	1	1		5	Clay with high plasticity

Note: * in case of GLTF laboratory tests each P_1, P_2 ratio was stated from one value of $E_{def,1}$, $E_{def,2}$ respectively and one corresponding value of M_{vd} measured closely to the place of static test execution, in case of field tests each P_1, P_2 ratio was stated from displayed number of averaged values of static moduli $E_{def,1}$, $E_{def,2}$ respectively and from displayed number of averaged values of dynamic moduli M_{vd} taken all of them close to each other in one specific section of prepared subgrade. Each row in the Table 2 represents averaged value of those moduli.

Table 2. Relationship of static and dynamic moduli based on their particular measured values

Tests	$E_{def,1}$, MPa	$E_{def,2}$, MPa	M_{vd}, MPa	$P_1 = \frac{E_{def,1}}{M_{vd}}$	$P_2 = \frac{E_{def,2}}{M_{vd}}$
Test set: No. 1 Soil tested: clay with intermediate plasticity	5.7	12.9	31.6	0.18	0.41
	6.4	14.4	29.6	0.22	0.49
	11.1	21.2	23.3	0.48	0.91
	11.2	20.1	27.7	0.40	0.73
	11.3	22.3	26.1	0.43	0.86
	13.2	25.9	24.7	0.54	1.05
	14.8	26.9	28.2	0.52	0.95
	10.4	16.5	28.9	0.36	0.57
	15.4	23.6	27.4	0.56	0.86
	15.2	25.6	31.8	0.48	0.81
	9.2	20.1	26.3	0.35	0.76
Test set: No. 2 Soil tested: sandy loam	14.9	27.1	27.6	0.54	0.98
	16.6	27.4	27.2	0.61	1.01
	20.4	30.4	29.7	0.69	1.02
	15.3	23.7	26.9	0.57	0.88
	23.1	41.4	30.2	0.77	1.37
	26.6	45.1	35.5	0.75	1.27
	20.8	40.3	33.0	0.63	1.22
	26.1	43.3	32.2	0.81	1.35
Test set: No. 3 Soil tested: gravel with fine soil impurity	24.5	40.2	59.1	0.41	0.68
	21.6	43.5	55.6	0.39	0.78
	31.5	45.7	43.2	0.73	1.06
	24.8	43.4	48.3	0.51	0.90
	34.4	62.9	58.0	0.59	1.08
	23.7	48.8	42.2	0.56	1.16
	34.2	64.2	52.7	0.65	1.22
	24.0	50.4	48.5	0.49	1.04
Test set: No. 4 Soil tested: loam gravel	45.8	93.1	52.7	0.87	1.77
	27.1	64.1	51.9	0.52	1.24
	41.3	83.2	79.9	0.52	1.04
	40.3	84.4	70.6	0.57	1.20
	34.4	77.0	47.7	0.72	1.61
	43.7	98.3	71.2	0.61	1.38
	33.1	69.9	62.0	0.53	1.13
	40.3	98.2	65.9	0.61	1.49
	30.5	62.1	73.1	0.42	0.85
	37.6	74.9	57.1	0.66	1.31
	32.8	85.2	55.4	0.59	1.54
	36.4	74.3	59.3	0.61	1.25
	32.0	72.5	74.4	0.43	0.97
	44.9	91.0	64.9	0.69	1.40
Test set: No. 5 Soil tested: loam gravel	32.4	70.6	41.2	0.79	1.71
	28.3	68.2	48.5	0.58	1.41
	35.1	73.4	46.3	0.76	1.58
	43.2	112.6	53.2	0.81	2.12
Test set: No. 6 Soil tested: gravel well-graded	32.7	53.1	41.2	0.79	1.29
	36.5	53.1	58.5	0.62	0.91
	31.3	48.4	68.2	0.46	0.71
	35.4	56.9	41.3	0.86	1.38
	35.9	55.0	43.9	0.82	1.25
	29.8	55.4	45.9	0.65	1.21
	34.4	54.6	42.2	0.82	1.29
	27.5	48.3	40.1	0.68	1.20
	27.8	51.6	40.2	0.69	1.28

Continued Table 2

Test set: No. 7	9.8	15.3	26.7	0.37	0.57
	9.5	13.7	23.5	0.40	0.58
Soil tested: clay with high plasticity	8.4	13.0	16.6	0.51	0.78
	10.3	14.9	30.4	0.34	0.49
	9.7	14.4	25.7	0.38	0.56

Table 3. Average values of ratios obtained from Table 2

Parameter	Kind of soil					
	Clay with high plasticity	Clay with intermediate plasticity	Sandy loam	Loam gravel	Gravel with fine soil impurity	Gravel well graded
Number of tests	5*	11	8	18*	8*	9*
Average ratio P_1	0.40	0.41	0.67	0.63	0.54	0.71
Sampling deviation of ratio P_1	0.07	0.13	0.10	0.13	0.12	0.13
Average ratio P_2	0.60	0.76	1.14	1.39	0.99	1.17
Sampling deviation of ratio P_2	0.11	0.20	0.19	0.31	0.19	0.22

Note: * these numbers of tests represent number of averaged tests according to Table 1.

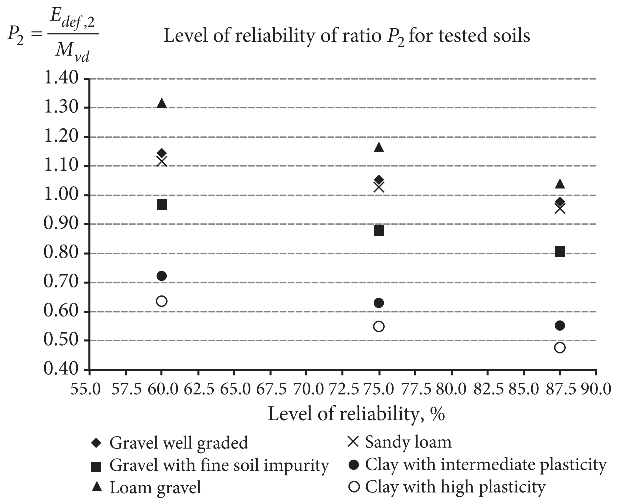

Fig. 8. Levels of reliability of obtained ratios of static and dynamic moduli

9. Conclusions

1. Similarity of formulas for moduli stated using static and dynamic loading tests and facts that both static and dynamic moduli have the same unit of measurement, static test takes about ten times more time for its execution as test using Light Falling Weight Deflectometer, and the Light Falling Weight Deflectometer test does not require a lorry for its execution as static test needs resulting in aspiration of contractors to replace static test with a dynamic one.

2. The paper demonstrates that correlation of static moduli with moduli obtained from Light Falling Weight Deflectometer is significantly related with the kind of soil, i.e., static and dynamic moduli have different values at all and relationship between them depends on at least the kind of tested soil. Therefore interchanging of static and dynamic moduli leads to the confusing results of earthworks quality evaluation. Reasons, why both moduli values differ, have been already published and explained and are not considered in the paper.

3. The use of Light Falling Weight Deflectometer for evaluation of deformation characteristics of subgrade is subject to correlation with static plate loading test which has to be done in each particular construction place on placed soil. Without the correlation moduli obtained from Light Falling Weight Deflectometer have a referential value which is able to compare the quality of earth works place to place within the area of particular construction place not to be taken as absolute value of soil deformation characteristics.

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References

Adam, C.; Adam, D.; Kopf, F.; Paulmichl, I. 2009. Computational Validation of Static and Dynamic Plate Load Tests with Respect to Specific European Standards, *Acta Geotechnica* 4(1): 35–55. http://dx.doi.org/10.1007/s11440-008-0081-0

Ahmed, A. T.; Khalid, H. A. 2011. Backcalculation Models to Evaluate Light Falling Weight Deflectometer Moduli of Road Foundation Layer Made with Bottom Ash Waste, *Transportation Research Record* 2227: 63–70. http://dx.doi.org/10.3141/2227-07

Alshibli, K. A.; Abu-Farsakh, M.; Seyman, E. 2005. Laboratory Evaluation of the Geogauge and Light Failing Weight Deflectometer as Construction Control Tools, *Journal of Materials in Civil Engineering* 17(5): 560–569. http://dx.doi.org/10.1061/(ASCE)0899-1561(2005)17:5(560)

Asli, C.; Feng, Z. Q.; Porcher, G.; Rincent, J. J. 2012. Back-Calculation of Elastic Modulus of Soil and Subgrade from Portable Falling Weight Deflectometer Measurements, *Engineering Structures* 34: 1–7. http://dx.doi.org/10.1016/j.engstruct.2011.10.011

Benedetto, A.; D'Amico, F.; Tosti, F. 2014. Improving Safety of Runway Overrun through the Correct Numerical Evaluation of Rutting in Cleared and Graded Areas, *Safety Science* 62: 326–338. http://dx.doi.org/10.1016/j.ssci.2013.09.008

Benedetto, A.; Tosti, F.; Di Domenico, L. 2012. Elliptic Model for Prediction of Deflections Induced by a Light Falling Weight Deflectometer, *Journal of Terramechanics* 49(1): 1–12. http://dx.doi.org/10.1016/j.jterra.2011.10.003

Floss, R. 1973. Bodenmechanische Gesichtspunkte bei Auswahl und Dimensionierung von Straßenbefestigungen [Soil Mechanic Viewpoint on Choosing and Design Pavement Stabilisation], *Straße und Autobahn* 24(1): 17–26.

Guzina, B. B.; Fata, S. N. 2002. A Study of Ground–Structure Interaction in Dynamic Plate Load Testing, *International Journal for Numerical and Analytical Methods in Geomechanics* 26(12): 1147–1166. http://dx.doi.org/10.1002/nag.239

Ji, R.; Siddiki, N.; Nantung, T.; Kim, D. 2014. Evaluation of Resilient Modulus of Subgrade and Base Materials in Indiana and its Implementation in MEPDG, *Scientific World Journal,* Article ID 372838. http://dx.doi.org/10.1155/2014/372838

Khattak, M.; Mohammad, L.; Yuan, F.; Abadie, C. 2012. Variability of In-Situ HMA Volumetric and Mechanistic Characteristics Using Non-Destructive Test (NDT): Case Study, *International Journal of Pavement Engineering* 13(2): 110–125. http://dx.doi.org/10.1080/10298436.2011.597858

Lacey, D.; Look, B.; Williams, D. 2013. Assessment of Relationship between Insitu Modulus Derived from DCP and LFWD Testing, in *Proc. of 5th International Young Geotechnical Engineers' Conference (iYGEC 2013)*, vol. 2. Ed. by Cui, Y. J.; Emeriault, F.; Cuira, F.; Ghabezloo, S.; Pereira, J. M.; Reboul, M.; Ravel, H.; Tang, A. M. August 31– September 1, France, Marne la Vallee, 379–382.

Liu, J.; Zhang, Y.; Luo, Y.; Li, Z.; Jiang, L. 2006. A Test Research on Relativity Between Dynamic and Static Elastic Modulus of Clay, in *Proc. of 2nd International Conference on Environmental and Engineering Geophysics: Geophysical Solutions for Environment and Engineering*, vol. 1. Ed. by Xu, Y.; Xia, J.; Chen, C. June 4–9, 2006, Wuhan, Peoples R China. Mounmouth Junction: Science Press USA Inc, 70–73. WOS:000238999600011

Mashinsky, E. I. 2003. Differences between Static and Dynamic Elastic Moduli of Rocks: Physical Causes, *Geologiya i Geofizika* 44(9): 953–959. WOS:000186191900010

Muller, W. B.; Roberts, J. 2013. Revised Approach to Assessing Traffic Speed Deflectometer Data and Field Validation of Deflection Bowl Predictions, *International Journal of Pavement Engineering* 14(4): 388–402. http://dx.doi.org/10.1080/10298436.2012.715646

Oh, J. H.; Fernando, E. G.; Lee, S. I.; Holzschuher, C. 2012. Correlation of Asphalt Concrete Layer Moduli Determined from Laboratory and Nondestructive Field Tests, *Journal of Transportation Engineering* 138(3): 361–370. http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000316

Pospisil, K. 2005. Die Vorhersehbarkeit des Verformungsmoduls [Modulus of Deformation Predictability], *Strasse und Autobahn* 56(6): 313–318.

Salour, F.; Erlingsson, S. 2013. Investigation of a Pavement Structural Behaviour during Spring Thaw Using Falling Weight Deflectometer, *Road Materials and Pavement Design* 14(1): 141–158. http://dx.doi.org/10.1080/14680629.2012.754600

Sulewska, M. J. 2012. The Control of Soil Compaction Degree by Means of LFWD, *The Baltic Journal of Road and Bridge Engineering* 7(1): 36–41. http://dx.doi.org/10.3846/bjrbe.2012.05

Shin, E. C. 2012a. Freezing and Bearing Capacity Characteristics of Road Foundations under Temperature Condition, *Journal of the Korean Geotechnical Society* 28(3): 5–14. http://dx.doi.org/10.7843/kgs.2012.28.3.5

Shin, E. C. 2012b. Freezing and Deflection Characteristics of Flexible Pavement Structure Using Frost Model Test, *Journal of the Korean Geosynthetics Society* 11(3): 27–35. http://dx.doi.org/10.12814/jkgss.2012.11.3.027

Tompai, Z. 2008. Conversion between Static and Dynamic Load Bearing Capacity Moduli and Introduction of Dynamic Target Values, *Civil Engineering* 52(2): 97–102. http://dx.doi.org/10.3311/pp.ci.2008-2.06

Vennapusa, P. K. R.; White, D. J.; Schram, S. 2013. Roller-Integrated Compaction Monitoring for Hot-Mix Asphalt Overlay Construction, *Journal of Transportation Engineering* 139(12): 1164–1173. http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000602

Vennapusa, P. K. R.; White, D. J.; Siekmeier, J.; Embacher, R. A. 2012. In Situ Mechanistic Characterisations of Granular Pavement Foundation Layers, *International Journal of Pavement Engineering* 13(1): 52–67. http://dx.doi.org/10.1080/10298436.2011.564281

Vennapusa, P. K. R.; White, D. J. 2009. Comparison of Light Weight Deflectometer Measurements for Pavement Foundation Materials, *Geotechnical Testing Journal* 32(3): 239–251. http://dx.doi.org/10.1520/GTJ101704

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