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# EXPERIMENTAL STUDY OF THE MODULUS OF DEFORMATION DETERMINED BY STATIC AND DYNAMIC PLATE LOAD TESTS

**SIRKO LEHMANN[1], STEFFEN LEPPLA[2], ARNOLDAS NORKUS[3*]**

[1] *Institute and Laboratory of Geotechnics, Darmstadt Technical University, Darmstadt, Germany*
[2] *Ingenieursozietät Professor Dr.-Ing. Katzenbach GmbH, Frankfurt am Main, Germany*
[3] *Laboratory of Geotechnics, Vilnius Gediminas Technical University, Vilnius, Lithuania*

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**Abstract.** Soil, or soil structure modulus of deformation, is one of the main design parameters for road engineering and traffic infrastructure design of, for example, highways, railways, runways and embankments. It is also the main soil improvement criterion. When creating any road structure with codified design resistance, one employs structural layers of certain thicknesses and modulus of deformation. Both values need to satisfy the minimum values in accordance with codified requirements. This paper analyzes correlations for the widely applied in engineering practice methods to determine the soil stiffness. The static test methods acknowledged to be exact enough for determining the modulus of deformation for the primary and secondary loadings. As dynamic test methods require significantly less time and financial resources, they are widely accepted in engineering practice. The dynamic methods determine only

* Corresponding author. E-mail: arnoldas.norkus@vgtu.lt

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the dynamic modulus of deformation. Design practice aims to relate it with the static modulus of deformation of the secondary loading. Many countries propose codified correlations, with differing levels of conservatism, to convert the dynamic modulus of deformation into the static one. Developed correlations between the results of the static plate load test and the dynamic plate load tests processed from own test results of different soils are presented and a comparative analysis with other proposed correlations is given.

**Keywords:** dynamic plate load test, gravel, improved cohesive soil, modulus of deformation, natural cohesive soil, sand, static plate load test.

## Introduction

The quality and economical effectiveness of pavement structures of any type of road depends on the rational distribution of the structural parameters of the pavement. The pavement structure consisting of certain layers is designed with an aim to carry a certain type and magnitude of loading. One of the main requirements towards road structures is design stiffness, expressed via the modulus of deformation on the top of the road. The extra requirements for the modulus of deformation and the minimum height for the pavement structural layers are introduced as well (see, e.g. in Lithuanian Road Administration (2007), Tompai (2008)). Another aim in designing road structures is using local soils (Bheemasetti, Pedarla, Puppala & Acharya 2015; Čygas, Laurinavičius, Pauliukaitė, Motiejūnas, Žiliūtė & Vaitkus, 2015; Köhler, Herald, Hering, 1998; Lithuanian Road Administration, 2007; Mair 2005; Mateos & Soares, 2014).

The stiffness on the top of the pavement structure is calculated by applying the developed techniques. They employ the unit modulus of deformation and the height of the pavement structural layers. An actual demand in engineering is to find the most rational pavement structure with minimum costs, based on testing different construction types. Experimental investigations were realized by Čygas, Laurinavičius, Vaitkus, Motiejūnas, & Bertulienė (2008). The investigation identified the layers of granite (4 cm) on the top, followed by dolomite (4 cm), crushed dolomite (20 cm, 150 MPa on top), sand (47 cm, 150 MPa on top) and the base (45 MPa on top). Different experimental pavement structures have been constructed and tested with the aim to find the most rational one, which conforms to the aforementioned minimum codified requirements.

The rational design of a pavement structure consisting of different pavement layers can be formulated as a mathematical optimization problem in terms of introduced required variables of the stress and strain state of the pavement structure. An objective function of the optimization problem can be formulated as, e.g. of minimum cost or another aim. Constraints of the problem describe the admissible stress and strain state of the pavement structure as well as the minimum road structure deflection on the top of the structure, when serviceability limit state dominates over ultimate limit state of the structure. Additional artificial requirements, listed in the codified requirements as, e.g. minimum heights and moduli of deformation of the pavement structural layers, can be included into the set of problem constraints as well. A single solution conforming the global minimum for the optimization problem is obtained when the objective function is convex and the problem constraints form the convex domain of variables. Otherwise, only the local minimum/s of problem can be obtained, respectively. The price of each volume unit of structural layers, their unit stiffness as well as the minimum heights of structural layers are prescribed values of the optimization problem. The solvers for mathematical programming and relevant analysis methods apply for considering and interpretation of obtained solution of the optimization problem. The solution of the optimization problem directly yields the rational "theoretical" solution of the pavement structure. The determined rational "theoretical" pavement structure can be realized practically, and its resistance can be verified in situ. Compliance with test results can be verified by solving the analysis problem (mathematical programming methods can be applied as well) introducing the actual parameters (modulus of deformation and heights of structural layers) measured during the construction process of the pavement structure.

As mentioned before, the modulus of deformation is the main parameter in solving the problem. Thus, for practical needs it is necessary to have a wide range of parameters corresponding to different types of layers at your disposal. Fast and low-cost field tests are required for identification of the stiffness of compacted soil layers. Therefore, the static plate load test and the dynamic plate load test are widely applied in engineering practice. The static load test delivers the modulus of deformation for the first loading and the secondary loading (reloading). The dynamic test delivers the single dynamic modulus of deformation. The static and the dynamic load tests aim to measure the soil response parameters, so as to realize different deformation stages. A correlation between the processed results of both test types should be defined properly as it is of great use in engineering design and quality control.

The impact on soil compaction is different for static and dynamic tests. Hence, the deformation modulus processed from these test results represents different measured resistances. Thus, proper interpretation and correlation of static and dynamic deformation is required. Due to the complexity of the problem, the correlation of static and dynamic tests is developed empirically. It should be noted that actual resistance measures of road structures during their load bearing time depend also on coupled effects due to movable loadings and reloadings. Therefore, the developed correlations for deformation moduli processed from the static and dynamic loading tests for single loading-unloading and loading cases should be applied carefully, applying correction factors for obtaining the deformation moduli in case of repeated loadings.

The dynamic plate load test is recognized as the most rational method (ensuring time and financial savings) to determine the modulus of deformation of the soil layers. The stationary falling weight deflectometer (FWD) test was initially used for this purpose. Later, the traffic speed deflectometer (TSD) test, as less effected by disturbing factors, was implemented. It is now actively replacing the FWD test due to the obvious advantages for selecting the necessary data. Zofka, Sudyka, Maliszewski, Harasim, & Sybilski (2014) proposed an alternative approach for interpreting data of TSD test measures. Nasimifar, Thyagarajan, Chaudhari, & Sivaneswaran (2019) developed the approach evaluating the pavement structural capacity based on TSD test measures in agreement with analogous results processed by FWD test and the AASHTO (2017) test methods. Elseifi, Zihan, & Icenogle (2019) proposed the approach to utilize TSD test measurements for back-calculation analysis. Levenberg, Pettinari, Baltzer, & Christensen (2018) proposed the deflection index for assessing the TSD data. As loading types for FWD and TSD tests differ, a certain correlation method for resistance parameters should be developed. Muller & Roberts (2013) presented a revised approach of TSD test data analysis for deflection bowl predictions and clear correlation with the predictions of the processed FWD test data results.

Performing the static plate load test (e.g. FWD test) requires more effort with regard to qualification, time, and processing of results, than performing the dynamic plate load test. Therefore, the general approach is to apply the dynamic plate load test for determination of the dynamic modulus of deformation and apply the developed correlation with the relevant modulus of deformation processed from the static plate load test results. Such correlations for several soil types were reported in, e.g. guidelines and recommendations:

1) FGSV (2009a, 2009b) for sands and gravels: DB Netz AG (1997), FGSV (2009a, 2012), FSV (2008), Gütegemeinschaft Leitungstiefbau e.V, LAKD (1995), Landesbetrieb Straßenbau Nordrhein-Westfalen (2006), Zorn Instruments (2002);
2) for natural cohesive soils: DB Netz AG (1997), Gütegemeinschaft Leitungstiefbau e.V.; cohesive soils improved by lime: DB Netz AG (1997).

Meanwhile, several significant investigations aimed at deriving analogous correlations of the dynamic modulus of deformation versus the static modulus of deformation have been carried out (Adam & Kopf, 2003; Bertuliene, 2011; Kopf & Erdmann, 2005; Kopf, Adam, & Paulmichl, 2005a, 2005b; Schmidt & Rumpelt, 2009; Tompai, 2008; Weingart, 2003).

Investigations in this field are in high demand as employment of reliable correlations ensures significant time and cost savings for large construction projects, as described in Reichl, Michels, Schäfer, & Spang (2013). The current study aims to conduct the static and dynamic plate load test for different soil types and perform suitability analyses of the obtained results against the proposed correlations of the dynamic and static modulus of deformation.

## 1. Definition of the modulus of deformation defined by dynamic and static plate load tests

The static plate load test is conducted according to the procedures described in DIN 18134:2012 (Deutsches Institut für Normung e.V., 2012), LST 1360.5:1995 (Lithuanian Standards Board, 2019). The plate is incrementally loaded up to a fixed magnitude of pressure and then gradually unloaded and reloaded. At every load step, the settlement of the load plate is measured. The first load vs. settlement graph for characterizing initial resistance serves for determining the secant modulus of deformation $E_{v1}$. The second load vs. the settlement graph for characterizing unloading-reloading resistance serves for determining the secant modulus of deformation $E_{v2}$ (see both graphs in Figure 1). The aforementioned modulus of deformation is determined for the linearized

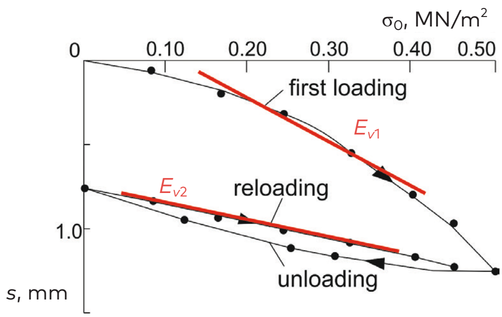


**Figure 1.** Load vs. settlement graphs for loading, unloading and reloading of static plate load test (after DIN 18134:2012; LST 1360.5:1995)

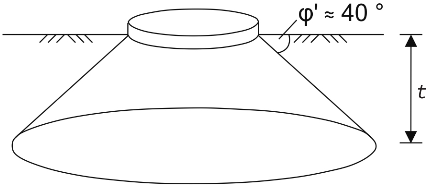


**Figure 2.** Approximate deformed soil volume subjected to static and dynamic plate load tests

path of $0.3\sigma_{max}$ and $0.7\sigma_{max}$, where $\sigma_{max} = 0.5$ MPa is the maximum of the applied pressure to soil via the loading plate. Both values refer to the static modulus of deformation. The ratio of $E_{v2}/E_{v1}$ represents the rate of compaction for influenced depth $t$ from the soil surface (Figure 2), in which ψ depends on the angle of internal friction of the soil layer. Depth $t$ is usually less than 1 m for static and dynamic plate load tests due to the angle of the internal friction. In different guidelines and specifications, the minimum magnitudes for the modulus of deformation $E_{v1}$ and $E_{v2}$ and proposed relations of $E_{v1}$ versus $E_{v2}$ are defined. Note that some of them, as, e.g. in FGSV, 2009a, relate to the proposed correlations combined with the compaction rate $D_{pr} = \rho_d/\rho_{Pr}$, where $\rho_d$ and $\rho_{Pr}$ are dry and Proctor soil densities, respectively.

The dynamic modulus of deformation $E_{vd}$ is defined by measuring average (3 tests) plate settlements from the impact (dynamic) load. Dynamic loading is induced by a falling drop weight, which is released from a reference height on a bar connected to the load plate. $E_{vd}$ is then defined by employing the empirical relation. So far, contrary to the static plate load test, no standards for the equipment and performance of the dynamic plate load test are available. Only some guidelines, such as FGSV (2003) and LAKD (1995), exist. Therefore, requirements for $E_{vd}$ magnitudes are rarely proposed and investigations in the field last for approximately 20 years, contrary to investigations on characterizing $E_{v1}$ and $E_{v2}$, which last for several decades.

## 2. Performance comparison of static and dynamic plate load tests

The static plate load test uses a counterweight, which must be heavy enough to ensure reliable performance (the experimental setup is given in Figure 3). The counterweight of a loaded truck or trailer may be used. The accuracy of test results is dependent upon the sensitivity

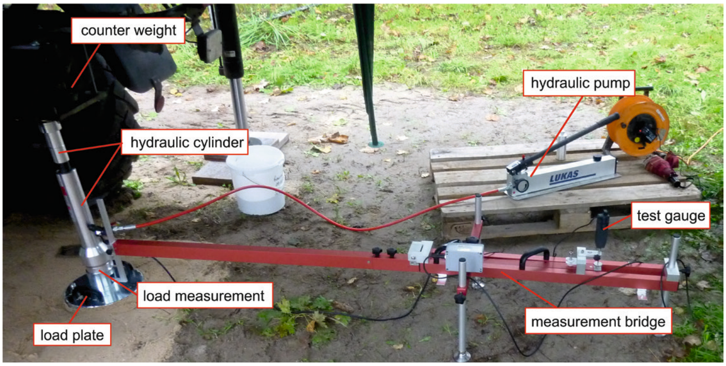


**Figure 3.** Experimental setup for a static plate load test

of readings, which requires qualified staff. One test lasts approximately 1.5 hours.

The experimental setup of the dynamic plate load test (Figure 4) is easy to transport and use. As no counterweight is necessary, tests can also be performed in limited spaces, such as excavations, trenches, etc.

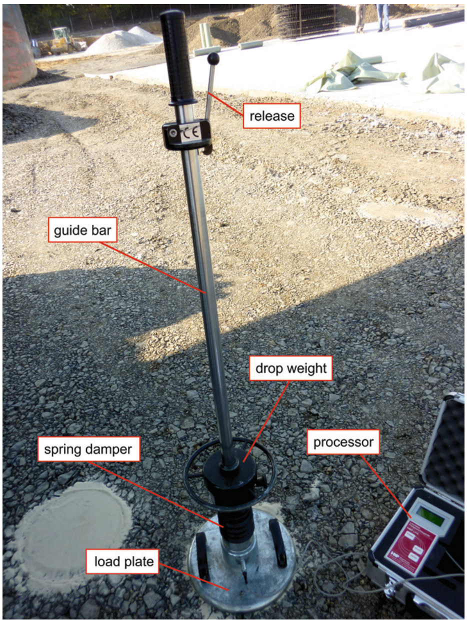


**Figure 4.** Experimental setup for a dynamic plate load test

**Table 1. Parameters and resources required for performing the static and dynamic plate load tests**

| | Static plate load test | Dynamic plate load test |
|---|---|---|
| **Time / test costs / investment** | appr. 1/2 h (without preparation)<br>appr. 100 EUR<br>appr. 3500 EUR net | appr. 5 min<br>appr. 50 EUR<br>appr. 5000 EUR net |
| **Diameter d** | 300 mm | 300 mm |
| **Measurement depth** | appr. 600 mm | appr. 600 mm |
| **Geometrical boundary conditions** | counterweight for hydraulic jack | almost none |
| **Field of application** | • 0° to 40 °C<br>• non-cohesive, soft to liquid material<br>• max. grain size is 1/4 of the diameter of the load plate and<br>• percentage of grains >63 mm must be insignificant | |
| **Preparation** | complex | easy |
| **Sensitiveness to vibrations** | very high as the test cannot be interrupted | high due to sensitive measurement devices |
| **Additional costs** | costs for the counterweight | – |
| **Maintenance** | once per year | once per year |
| **Results** | $E_{v1}$, $E_{v2}$, $E_{v2}/E_{v1}$ | $E_{vd}$ |

Both load tests can be conducted in coarse, non-cohesive soils, or fine soils of liquidity index (consistency) $I_C$ > 0.75 (Deutsches Institut für Normung e.V., 2012; FGSV, 2003; LAKD, 1995). As soil response is sensitive to unevenness of contact, no stones with a size of more than 0.25 of the load plate diameter should be at the plate-soil contact surface. A thin layer of dry sand may be added to ensure flat contact of the soil surface to the load plate. Measuring devices must be calibrated regularly. Equipment for static and dynamic plate load tests is very sensitive to vibrations. Therefore, it must be ensured that no external vibrations are caused near the test places, such as those, which can occur during compaction works or in the presence of heavy transport traffic. In situ tests should be performed at the earliest 24 hours after the compaction works have been completed. The main parameters and resources employed to compare the expenses of both kinds of tests are summarized in Table 1.

## 3. Correlations for static and dynamic modulus of deformation

As performing the dynamic plate load test requires significantly less resources, the focus of the research is made on the development of reliable and rational relationships between the static and the dynamic modulus of deformation. Many specifications and guidelines propose different empirical correlations, combining the values $E_{v1}$, $E_{v2}$, $E_{\mathrm{vd}}$, $E_{v2}/E_{v1}$, and $D_{\mathrm{pr}}$ for different types of soil. In (Bertuliene, 2011; Bertulienė, Juknevičiūtė-Žilinskienė, Sivilevičius, & Laurinavičius, 2018) it was determined that processed correlations depend on testing techniques. Using an empirical approach to obtain correlations for the aforementioned values, one must evaluate not only different compaction mechanisms of soil developed during static and dynamic plate tests, but should also consider the factor of different testing equipment parameters and technology employed for the same type of test (Bertuliene, 2011). The combination of initial correlations with an aim to obtain new correlations as, e.g. $E_{v1}$ versus $E_{\mathrm{vd}}$ or $E_{v2}/E_{v1}$ versus $E_{\mathrm{vd}}$, definitely decreases the accuracy of new correlations.

The correlation $E_{v2}$ versus $E_{\mathrm{vd}}$ is common in engineering practice. Eq. (1) shows the linear correlation often applied in engineering practice (e.g. proposed in FGSV (2009a)):

$$E_{v2} = 2E_{\mathrm{vd}}. \tag{1}$$

In the following section, the results of static and dynamic plate load tests are presented for the same types of soil. The tests were performed at Technische Universität Darmstadt, Germany, for different types of coarse and fine soils. The processed test data are illustrated via red dots in Figures 5–8 below. In addition, the proposed correlations from several guidelines and specifications are displayed.

### 3.1. Correlations for sand

The proposed correlations of $E_{v2}$ versus $E_{\mathrm{vd}}$ for sand are given in Figure 5. The values of Eq. (1) are displayed close to the middle of the graphs and fit with the correlations presented in Gütegemeinschaft Leitungstiefbau e.V., FGSV (2012), Schmidt & Rumpelt (2009), Zorn Instruments (2002), and are close to FGSV (2009b). The correlations presented in DB Netz AG (1997), FGSV (2009a), Kopf & Erdmann (2005), and Landesbetrieb Straßenbau Nordrhein-Westfalen (2006) are significantly different when compared to correlation (Eq. (1)). The processed tests results obtained at Technische Universität Darmstadt fit well with correlation (Eq. (1)).

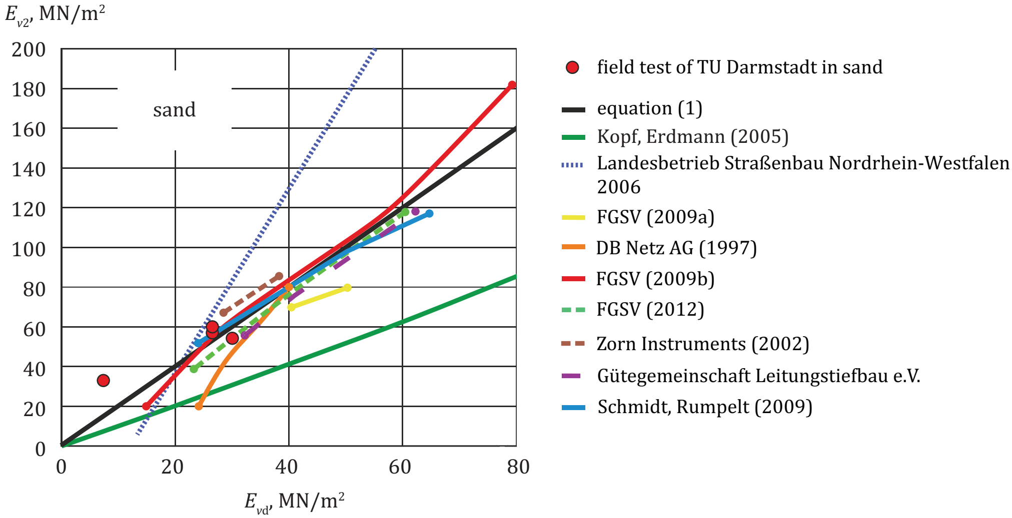


**Figure 5.** Correlations for sand

## 3.2. Correlations for gravel

The proposed correlations of $E_{v2}$ versus $E_{vd}$ for gravel are given in Figure 6. Correlation (Eq. (1)) appears almost in the middle of the graph and fits with the correlations presented in FGSV (2009a, 2012),

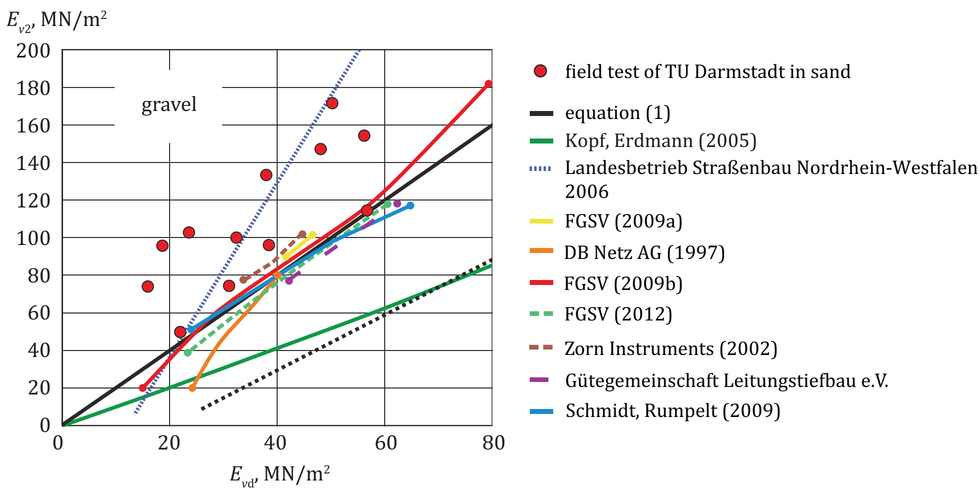


**Figure 6.** Correlations for gravel

Gütegemeinschaft Leitungstiefbau e.V., Schmidt & Rumpelt (2009), Zorn Instruments (2002), and is close to the correlation presented in FGSV (2009b). The correlations presented in Bertuliene (2011), DB Netz AG (1997), Kopf & Erdmann (2005), and Landesbetrieb Straßenbau Nordrhein-Westfalen (2006) are significantly different when compared to correlation (Eq. (1)). The test results obtained at Technische Universität Darmstadt roughly fit with the correlations presented in Landesbetrieb Straßenbau Nordrhein-Westfalen (2006).

## 3.3. Correlations for cohesive (partially fine) soil

The proposed correlations of $E_{v2}$ versus $E_{vd}$ for cohesive (partially fine) soil are given in Figure 7. Correlation (Eq. (1)) is almost in the middle of the plot and fits with the correlations presented in FGSV (2012), Schmidt & Rumpelt (2009), and is close to correlations presented in DB Netz AG (1997), FGSV (2009b), and Gütegemeinschaft Leitungstiefbau e.V. The correlations presented in Landesbetrieb Straßenbau Nordrhein-Westfalen (2006) and Kopf & Erdmann (2005) are significantly different when compared to correlation (Eq. (1)). The limited number of test results obtained at Technische Universität Darmstadt cannot ensure the reliable correlation and the subsequent comparison with the proposed above-mentioned correlations.

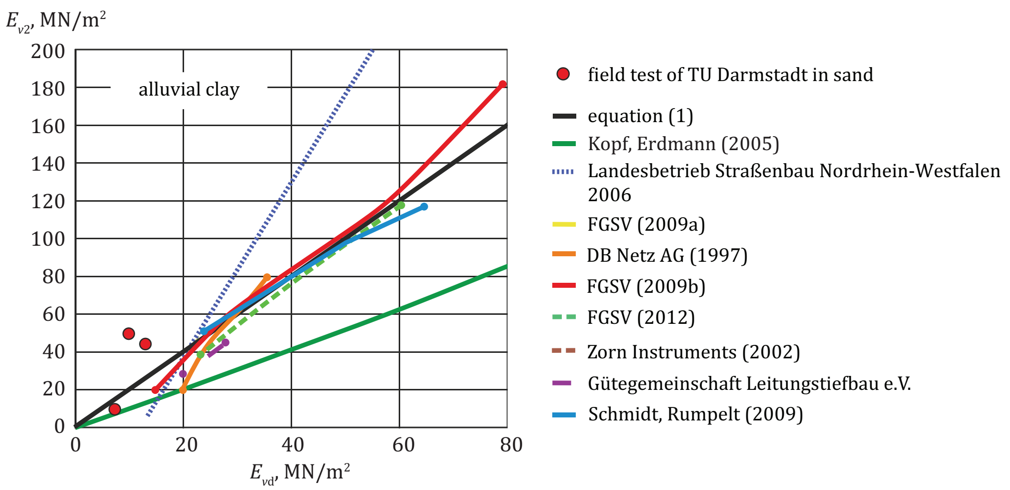


**Figure 7.** Correlations for cohesive soil

## 3.4. Correlations for cohesive (partially fine) soil, improved by granular calcium carbonate

The proposed correlations of $E_{v2}$ versus $E_{vd}$ for cohesive (partially fine) soil, improved by granular calcium carbonate, are given in Figure 8. Due to the chemical reactions of calcium carbonate and the resulting time effect for stiffness increment, these correlations are processed for two time intervals, namely, for ≤48 hours and >48 hours. Correlation (Eq. (1)) is plotted almost in the middle and fits with the correlations presented in FGSV (2012), Schmidt & Rumpelt (2009), and is close to FGSV (2009b). The correlations presented in DB Netz AG (1997), Kopf & Erdmann (2005), and Landesbetrieb Straßenbau Nordrhein-Westfalen (2006) are significantly different when compared to correlation (Eq. (1)). The test results obtained at Technische Universität Darmstadt fit well with correlation (Eq. (1)) and the correlation presented in Kopf & Erdmann (2005).

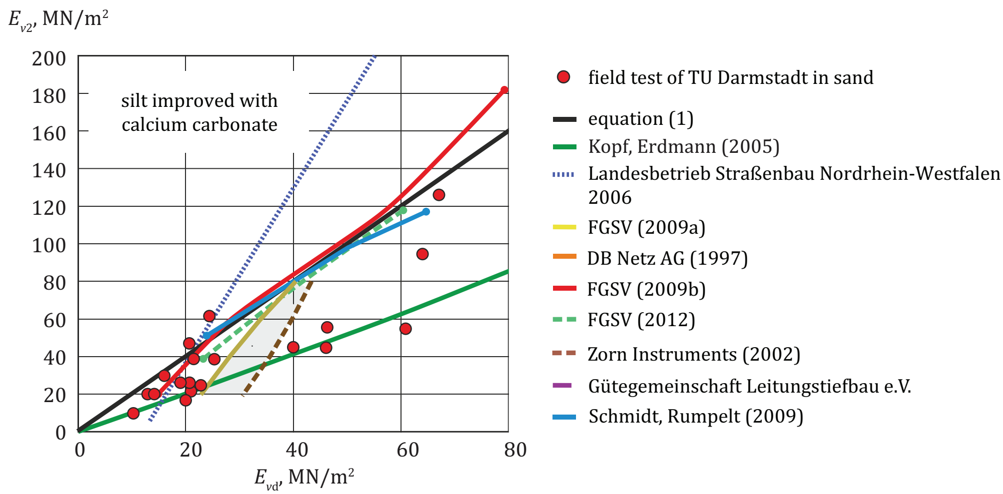


**Figure 8.** Correlations for cohesive soil improved with fine granular calcium carbonate

## Concluding remarks

This paper examined the static and dynamic plate load in situ tests performed at Technische Universität Darmstadt with various types of soil with the aim to determine deformation moduli for unloading-reloading resistance and the dynamic deformation modulus. The comparative analysis of obtained results performed regarding the correlations of static deformation modulus versus dynamic deformation modulus are presented in different guidelines, specifications, and research papers. The analysis shows that no reliable correlations for the static versus dynamic soil modulus can be proposed for engineering practice. This statement is valid for the correlation of single test results, but not for boundary values, which are given in several guidelines and specifications. The research process continued in order to determine the correlations for static versus dynamic deformation modulus, in terms of boundary values.

The main reasons for discrepancies in the scattered results are naturally varying soil parameters, application of different test methods and test results, as well as the lack of other parameters, which are needed to develop more exact correlations. If a certain correlation is necessary, the authors recommend performing the static and dynamic plate load tests to develop the reliable correlation for the local site soil.

However, considering significant savings in time and cost, it is economically useful to perform the static and dynamic plate load tests at certain sites and develop specific correlations based on the processed results.

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