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# Reloading Modulus Estimation Based on Static and Dynamic Plate Load Tests Carried out on Unpaved Forest Roads

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## ABSTRACT

This paper presents the results of comparative studies of strain modulus from static (PLT) and dynamic (LWD) plate testing. The tests were conducted on 9 sections of forest roads with different surfaces made of unbound aggregates. They produced 140 – element sets of results, including values of reloading modulus ($E_2$) and dynamic modulus of deformation determined using 10 and 15 kg drop weights ($Evd_{10}$ and $Evd_{15}$). An attempt was made to determine the relationship between the values of the moduli from tests with LWD loads (10 or 15 kg) and PLT, which would allow to determine the values of reloading modulus based on the dynamic modulus values. The analysis of the test results revealed that the values of the dynamic moduli are characterized by lower variability than those obtained from static testing and that from the engineering point of view there is no significant relationship between the sets of results of the subgrade deformability tests made with dynamic and static plates. The analysis of the results confirmed a simple relationship that allows for a qualitative assessment of subgrade deformability defined by the values of reloading modulus PLT tests based on the results of LWD tests with a 10 kg drop weight. The assessment error did not exceed 7% in this case. An analogous relationship was revealed for the results of LWD tests with a 15 kg drop weight. In this case, the assessment error did not exceed 6%. The results of the LWD tests can be used to provide a qualitative assessment of the deformability of subgrade, but the PLT tests are required for its quantitative assessment.

**Keywords:** LWD, PLT, static plate load test, forest roads, correlation between PLT and LWD.

## INTRODUCTION

In today's world, it is important to ensure a safe and stable flow of raw materials. One of the most commonly used ones is timber harvested from forests. The most important areas of its use are construction – building elements (timber framing, framed floors, window and door frames), industry (chipboard, pallets, cardboard, paper), architecture (furniture, panelling, ceilings, panels, boards) and arts (e.g. musical instruments) or energy production (fuel) [1]. A well-developed road network is important to facilitate timber harvesting for the industry. Forest roads provide access to the harvesting areas and enable the transport of timber from the forest to manufacturing plants. The proper efficiency of forestry and forest industry operations cannot be achieved without a suitable forest road network. By making forest resources available for efficient economic activities, it also enables their protection and the fulfilment of increasingly important social needs [2]. It is also not insignificant that forest roads are often transport routes complementing the public road network.

The forest road network can only fulfil its function properly if it is adapted to its task in terms of road density, load-bearing capacity and geometry parameters. Forest roads are so-called low volume roads, which are generally characterized by the lowest performance standards. The load-bearing capacity of forest roads varies considerably depending on the weather and season, as they are usually made of low-quality material and the layers laid may be mixed with the soil [3]. They are often poorly constructed and consist of only one layer (base course) or two layers (base course, surface/wearing course). In most cases, forest roads have a surface of unbound aggregate. Underneath are granular embankments made with the use of local, environmentally friendly materials in an economical way, not to disturb the forest ecosystem and to minimise the environmental impact [4, 5].

According to the Central Statistical Office, at the end of 2022 the forest area in Poland was 9.27 million hectares, which corresponds to a forest cover of 29.7% [6]. The State Forests – National Forest Holding (the main administrator of forest areas in Poland) takes care of almost 107,000 km of internal roads of different ranks in the transport networks of forest transport areas. The vast majority of them have a native surface (71%). Surfaces made of gravel, crushed stone, cinders, cobblestones, etc. are found on about 20% of the total length of all forest roads, and bituminous/concrete surfaces account for only 9% of their length. Natural aggregates obtained from the crushing of solid rock, with particle sizes of 0/4 mm, 4/31 mm, 31.5/63.0 mm (alternatively slightly more cost-effective road aggregates with particle sizes of 0/31.5 mm and 0/63.0 mm) [7].

Mobile devices for continuous monitoring of load-bearing capacity are currently being sought, to be used in the planning of timber transports to prevent rutting, especially for transports over a low-volume road network during the spring and autumn season, when the weather conditions strongly affect the condition of forest roads. The results of the measurements can be used to prevent road damage and minimise ongoing maintenance costs [3].

This paper attempts to determine the relationship between the typical static load plate test (PLT) and the increasingly popular dynamic plate test (LWD).

## ASPECTS OF THE BEARING CAPACITY TESTING WITH THE USE OF RIGID PLATE

The reliability of road surfaces depends on the load-bearing capacity of the individual construction layers and the subsoil. The modulus of elasticity of a material is used to describe its stress-strain behaviour and its response to traffic loading. Therefore, the determination of the in-situ modulus of elasticity is of crucial importance for the characterization of road pavement and its correct structural design [8].

In the literature on geotechnical investigations, quality control of earthworks and road construction, the topic of bearing capacity measurements with rigid plates has received much attention.

### The methodology of static plate load test (PLT)

The method of static surveying with rigid plates is widely used in road and railway construction and is used as a basic test to determine the bearing capacity and deformation state of the subsoil. Repeated measurements provide direct geotechnical parameters for determining the bearing capacity and deformability of the subsoil – the values of the initial loading and reloading moduli. In addition, the compaction state of the investigated subsoil can be determined indirectly from the measurements. This is done using the values of the deformation index ($E_2/E_1$ modulus ratio), from which the value of the compaction index can be estimated [9, 10].

The test device has a standardised design and a standardised test procedure as described in the standards and regulations [9, 11]. The test set consists of a rigid steel plate with a diameter of 0.3 m, a pump with hydraulic drive, a stand and measuring sensors to determine the plate pressures and displacements (Figure 1). The test setup can be equipped with three displacement sensors mounted on the plate bars or with one sensor with central mounting on a tripod. The measuring sensors should be calibrated at regular intervals by authorised bodies. The device has no electronic circuits and therefore requires no electrical supply, and the test results are not affected by interference from electromagnetic fields. Performing the determinations requires the use of a counterweight with sufficient mass, which can be a suitable construction machine, e.g. a backhoe loader, a roller or a loaded lorry (Figure 1). The need to use a counterweight makes it difficult to carry out measurements in confined areas (e.g. in narrow excavations).

Before starting the test, the plate must be properly levelled and the device positioned so that no uncontrolled movements (e.g. due to the counterweight slipping) occur while it is being carried out. The static plate load test procedure

**Figure 1.** Static plate load test on a forest road – test device

is complex, time-consuming and error-prone, so the measurements should be carried out by qualified personnel. The test consists of performing the loading and unloading cycle twice (Figure 2).

The load is increased in steps of 0.05 MPa, whereby the displacement of the plate must be stabilized after each change in the load value until the maximum load is reached. The value of the maximum load depends on the type of layer to be tested and its desired working load. The load is removed in the same way, reducing the load on the plate by 0.10 MPa in each successive step until it is completely removed. During the measurements, care must be taken to ensure that the plate and tripod are not moved in an uncontrolled manner, as this can affect the results. In extreme cases, this can lead to the measurement having to be halted and repeated at another, neighbouring point. It is not possible to carry out successive measurements at the same location, as the compaction state of the soil changes irreversibly during the performance of the tests with successive loads. The person carrying out the measurements can intervene in the test procedure, at any time, by checking the setting of the plate, the tripod and the measuring sensors and selecting the appropriate value of the set load. Measurement errors can occur during the test, e.g. due to improper execution of the loading and unloading cycles, a lack of stabilization of the plate settlements during the successive loading steps or an incorrect reading of the values from the measuring sensors, especially

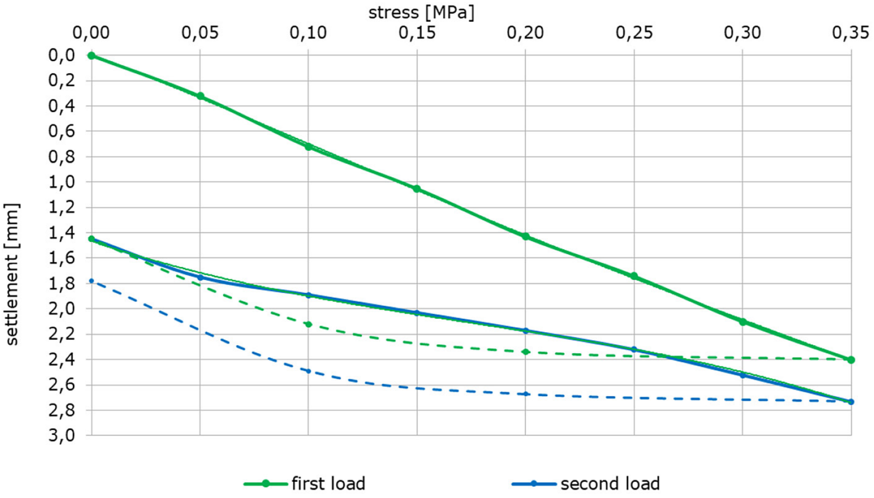

**Figure 2.** Static plate load test on a forest road – example of a plate settlement diagram

if the recorded settlement values are significant. During the execution of the test cycles, construction work in the vicinity of the measuring station, e.g. compaction of soil and rock layers, traffic of machines and vehicles, should be temporarily interrupted, so that the measurement results are not influenced by dynamic effects of the operation of machines and equipment. Due to the lengthy process of stabilizing the displacements of the plate, especially when investigating highly deformable substrates, the measurement results are only available after a long period of time. The calculation of the measurement results – the values of the deformation modulus and the deformation index – is easy to check using uncomplicated calculation formulae and can be carried out on site. The values for the geotechnical parameters obtained directly from the tests form the basis for the acceptance tests. By evaluating the results of these tests, designers and site managers can use typical catalogues or standardised solutions to determine the correct pavement design or the appropriate reinforcement of the subsoil. The acceptance requirements for the deformation moduli ($E_1$, $E_2$) and deformation index ($I_o$) values determined by the tests for the subgrade and pavement structures can be determined individually by the designers, especially in complex cases or for non-standardised designs of pavement structures or their reinforcement [10]. PLT tests are standardized in many countries, e.g. Poland [9, 12], Germany [13], Great Britain [14], USA [15].

## The methodology of dynamic plate load test (with the application of the LWD)

The limitations of static plate testing have contributed to the development and growing popularity of dynamic plate testing. The measurement method is monitored by the device's software, no counterweight is required during the test and the results are available within a few minutes. As a result of the determinations performed, values of the dynamic deformation modulus ($E_{vd}$) and the ratio between the displacement of the plate and its pre-stressing speed ($s/v$) are obtained. The devices used come from different manufacturers and have different designs and procedures. A standard tester consists of a rigid steel plate with a diameter of 0.3 m equipped with an accelerometer and a spring element, a mechanical loading device with a weight of 10 or 15 kg and a measuring computer with internal memory for storing the results (Figure 3). The device requires an annual calibration by the manufacturer, which is usually combined with a software update of the measuring computer. Due to the electronic circuits used, the device requires a power supply and its operation may be disturbed by electromagnetic fields that are present in the vicinity of the tests performed, e.g. in the area of influence of high-voltage power lines. The device is not equipped with damage-prone hydraulic systems and additional measuring sensors. Due to the small size of the device, the measuring stations can also be set up in places that are difficult to access, e.g. in narrow excavations.

**Figure 3.** Dynamic plate load test on a forest road – test device

Furthermore, carrying out the measurements does not require any interruption to construction work, as the device is not susceptible to vibrations from moving vehicles, machinery and construction equipment. The test method is simple, it is monitored by the software of the measuring device and does not require qualified personnel. The measurements with the dynamic plate are performed in a short time and the results are available after just a few minutes (Figure 4). Due to the automation of the measurements, there is no possibility to change the test algorithm, no intervention of an external operator during the measurements is possible and it is difficult to verify the accuracy of the results obtained. In addition, the accuracy of the results depends on the accuracy of the calculation algorithms implemented in the device's software. The loads used (10 and 15 kg) allow a plate pressure of 0.10 and 0.15 MPa, respectively, which significantly limits the possibility of choosing the load according to the expected stresses of the tested layers and substrates and affects the depth of the plate's settlement [10].

## The methodology of dynamic plate load test (with the application of the LWD)

Stress testing of roads belongs to the category of in-situ non-destructive testing (NDT), which is becoming increasingly popular as it offers a quick and cost-effective assessment option. One of the main advantages of in-situ NDT techniques is that they better reflect actual field conditions, as laboratory testing mainly refers to artificial (simulated) environmental conditions that may not be representative of the field [16].

The development of a clear assessment is complicated by the different standards for conducting PLT tests in different countries. The differences include the maximum applied loads, the number of loading and unloading stages of the plate, the loading/unloading times in each stage or the load ranges used to calculate the modulus values [7]. In Poland, the following maximum load values are generally used for PLT tests (the pressure plate is placed directly on the layer to be tested [7, 9, 11, 12, 17]):

- 0.25 MPa – when testing the road subgrade or embankment;
- 0.35 MPa – when testing the layer(s) of the improved road subgrade;
- 0.45 MPa – when testing the layer(s) of the road base course;
- 0.55 MPa – when testing the entire road structure.

In LWD tests, the basic load is 0.1 MPa with a load of 10 kg and 0.15 MPa with a load of 15 kg. The load-bearing capacity, which is represented by the moduli $E_2$ and $E_{vd}$, indicates the resistance to deformation. It can be used interchangeably with the modulus of elasticity or modulus of subgrade reaction. It largely determines the

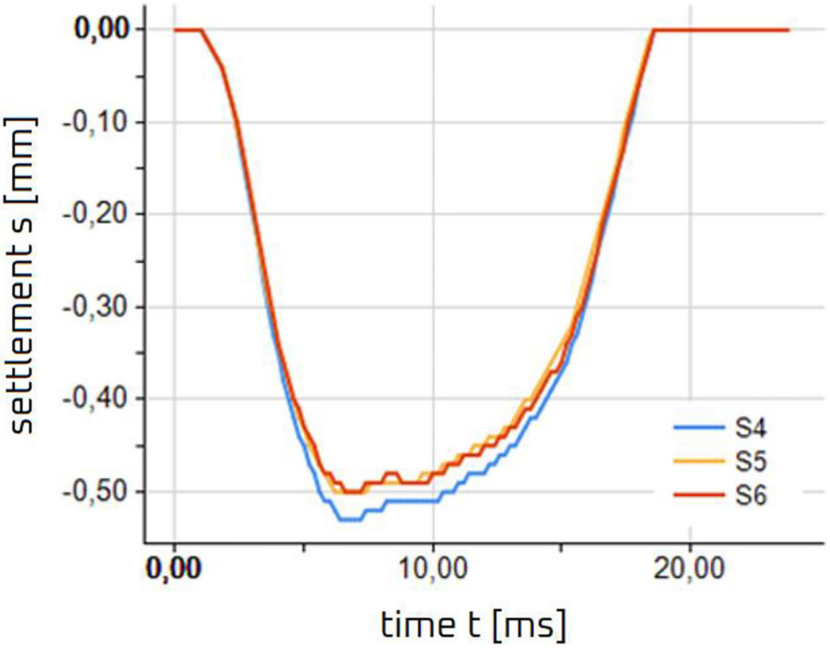

**Figure 4.** Dynamic plate load test on a forest road – example of a slab settlement diagram, S4, S5, S6 – 4th, 5th, 6th cycle of load test

deformation and displacement of the subgrade during loading and unloading [18]. According to [19], one reason for the different results and the difficulty in determining correlation constants between the PLT and LWD tests is the fact that the LWD device is currently not standardized; as a result, there are many commercially available designs that provide different values for deflection and modulus of elasticity.

Researchers [20–22] note that the lack of direct comparison between the results obtained with the two methods is, among other things, due to the different quality assessment and accuracy of the test results, and due to factors such as the varying drop height, the rigidity and size of the loading plate, the type of layers – aggregates/soils and the calculation method resulting from the location and the number and type of accelerometers or geophones, and the value of the contact stress under the plate [17]. In Poland, 0.3 m diameter plates with a set of one or three measuring sensors is usually used for PLT tests [11, 23]. For LWD tests, a 0.3 m plate and devices with an accelerometer and a fixed drop height with weights of 10 or 15 kg are used [11, 24].

Due to the use of the modulus calculation method based on the elastic half-space theory [25], which assumes that all underlying soil layers represent a homogeneous elastic material, the influence of the soil type and its properties on the impact surface of the loading plate is an important factor to be taken into consideration [23, 26]. Depending on the stress achieved, the impact range of the device can be between 2.7 and 4.2 measurement diameters (z/D in tests with a 0.3 m diameter plate [17]). Based on numerical analyses with the elastic half-space model [27], the influence under impact load in the area of influence of the LWD below the measuring plane is 2.66 plate diameters and in the horizontal plane represents a circle with the centre on the loading plate and whose diameter is twice as large. Subsequent in-situ tests [8] have shown that the depth of the PLT impact is twice the diameter of the load plate and it represents about 0.28 m for the LWD, which means that more than one layer can be measured during the test. Numerical calculations have shown that the difference between the two moduli becomes more pronounced as the layer thickness increases. For variations in soil type, where the layers are stiffer than the underlying soil, $E_{vd}$ is greater than $E_1$ and $E_2$ over the entire layer thickness. With a significant increase in layer thickness, the difference becomes smaller and finally the static load plate test results in a higher deformation modulus than the dynamic load plate test [28].

In addition to the variability of the soil, the influence of moisture content, capillarity and the height of the groundwater table have been identified as important factors where the deformation moduli are particularly different in comparison between water-saturated and dry conditions [29]. The modulus values are also influenced by primary stresses in the soil, history of previous loading, dewatering conditions, dispersion, heterogeneity and strain amplitude [30]. In addition, the mineralogical composition, the size and gradation of the individual particles and the shape of the individual particles also play an important role [31].

According to [30], the time of measurement has a significant effect on the value of the modulus. In static tests, the modulus of elasticity is stress divided by strain for slow-acting loads, while in the dynamic method the modulus is defined as stress divided by strain for short-term and fast-acting loads. It has also been pointed out that when measuring with both methods, care should be taken to avoid external vibrations near the test points, which can occur during compaction work or in the presence of heavy traffic, as the plate load testing equipment is very sensitive to vibrations, and the static load plate test method is more susceptible to vibrations [32]. An important technical factor is the influence of a flat surface under the plate – the LWD is more sensitive in the measurements [20]. It is therefore recommended to apply a thin layer of fine sand to the test point in accordance with the guidelines [33]. For layers reinforced with sand and aggregates, coarser layers increase the elastic deformation and reduce the total deformation in static measurements, while the opposite is true for dynamic testing. It is therefore difficult to obtain clear and generally valid correlations for the conversion of deformation results between the two methods [34].

The dynamic method does not take into account the effects of cyclic loading on the variability of the parameters of the layer to be tested, in particular the native subsoil. The method assumes that the layer is compacted after the third loading cycle and that the following three loads form the basis for the calculation of vertical displacements. The effect of re-compaction in the successive loading cycles, which has a significant influence on the recorded deflections and moduli of elasticity and thus on the fatigue life is ignored [35]. Static plate tests do not take into account non-linear stress propagation, the possibility of plastic yielding of substrate in the immediate vicinity of the test plate or the historical loading of the layers in question [28].

Summarizing the authors' own experiences in the field [10], it is possible to determine the advantages in favour of the selected type of test, as presented in Table 1. The performance of the LWD measurements is governed by regulations in many countries [21]. Countries with regulations governing the requirements for dynamic testing include: Switzerland [36], Germany [37], United Kingdom [38], United States [33, 39], Italy [40]. Other countries such as Latvia [32], Lithuania [41], the Czech Republic [5] and Romania [42] have not yet generally introduced testing to prove the correct execution of work.

In Poland, there are a number of research projects investigating the possibility of using the LWD tool as an alternative to the static PLT test. Detailed investigations and suitability for use only for non-cohesive soils were carried out by the Road and Bridge Research Institute in Warsaw (IBDiM) [24]. The first document to officially refer to the possibility of using the LWD tool was the Renovation Catalogue [11], which, however, was not officially adopted for use. Conversions specified by the manufacturer or based on German regulations [26, 43–46] do not work for all subgrade layers and structures. According to the authors, the lack of reproducibility of correlations common, for instance, for the USA, Great Britain or Germany, is also due to the geological structure and glaciation processes and to the considerable variability of soils in Central Europe.

In dynamic tests of bituminous pavements, it is possible to determine the seasonal changes in the stiffness of the structure during the spring thaw period [47, 48]. The measurements were only performed when the thickness of the bituminous layers was less than half of the LWD influence zone. The same tool can be used to easily indicate regions of insufficient bearing capacity in subsoil investigations to find locations for static tests carried out to check the covered layers as required by regulations [49].

**Table 1.** Advantages (marked in bold) of load-bearing capacity tests with static and dynamic plates [10]

| Static plate | Dynamic plate |
|---|---|
| **Uniform (standardised) device design.** | Manufacturer-dependent design. |
| **Uniform (standardised) test scheme.** | Manufacturer-dependent test scheme. |
| Complicated test scheme. | **Simple test procedure.** |
| Results after time-consuming testing. | **Results are obtained within minutes.** |
| **Test results are the basis for acceptance of the work.** | Test results do not form the basis for acceptance of structures. |
| **Methods for planning soil stabilization, paving structures based on direct test results.** | No methods to design soil reinforcement, paving structures based on direct determination results. |
| **Basic geotechnical parameters obtained directly from the test.** | Correlation relationships are required to determine the values of the basic geotechnical parameters. |
| **Simple calculation algorithm, easy verification of the correctness of the results obtained.** | The accuracy of the measurement depends on the accuracy of the calculation algorithms contained in the device software; no possibility to check the accuracy of the results obtained. |
| **Monitoring of the progress of the investigation and possible interventions during the investigations.** | Automated measurement, no possibility of intervention during the determination. |
| Counterweight required. | **No need to use counterweights.** |
| Sensitive to measurement errors. | **The test procedure is monitored by the device software.** |
| **Insensitive to electromagnetic fields.** | Possible sensitivity of the device to electromagnetic fields and risk of erroneous results. |
| Hydraulic system susceptible to interference. | **No hydraulic systems.** |
| Calibration of the measurement sensors required. | **Need to calibrate the device and update the software.** |
| **No power supply required.** | Electrically powered device susceptible to power failure during measurement. |
| Complicated operation. | **Simple operation.** |
| Difficult to carry out in narrow excavations. | **No restrictions for measurements in excavations.** |
| **Possibility of load selection depending on the type of layer/structure to be tested.** | Limited possibility of load selection depending on the type of layer/structure to be measured. |
| Requires interruption of work in the vicinity of the test rig. | **No restrictions during construction work near the measurement location.** |

With the LWD, more tests can be performed during the execution of a single PLT. Variability of the moduli can be represented graphically in the form of spatial information [50].

Many researchers have carried out comparative studies on different layers, including layers with aggregates [12, 26, 51], layers reinforced with geosynthetics [50–52] or layers improved with binders [8, 42, 53]. The most common benchmarking analysis with the use of the LWD involves the use of various field measurement devices, such as:

- FWD devices [3, 47, 54],
- Benkelman beam [27, 55, 56],
- CPTu static test [54],
- DPL dynamic penetrometer [57],
- DCP test (CBR assessment) [3, 20, 53, 54, 57–59],
- the most common comparative studies with the PLT static test [10, 22, 23, 28, 30, 41, 51, 53, 57].

## MATERIALS AND METHODS

This article compares the results of tests carried out using the PLT and LWD methods for different forest road surfaces. Similar studies were carried out, among others, by [3, 7, 49].

### Aim and scope of the study

The aim of this study was to determine the predictability of the values of the reloading modulus obtained from PLT measurements based on LWD measurements (Zorn, ZFG 3000 GPS) with the 10 and 15 kg drop weights. The load-bearing capacity of forest roads with unbound aggregate surfaces was tested. The research objective was defined as: Does the use of the Zorn ZFG 3000 GPS lightweight dynamic plate with a 10 and 15 kg drop weight in load-bearing capacity tests of forest road surfaces made of unbound aggregates allow for simple and accurate prediction of the values of the reloading modulus?

### Subject of the study

On 9 experimental forest road sections with different road surfaces, which were categorised into 3 groups (Figures 5, 6, 7), load capacity tests were carried out over several years using the following equipment:

1) The lightweight deflectometer ZFG 3000 GPS from Zorn Instruments with drop weights of 10 and 15 kg and a circular load plate with a diameter of 300 mm. The use of a 10 kg drop weight enables meaningful measurements in the range 15 MPa < $E_{vd}$ < 70 MPa, while a 15 kg weight supports the 70 MPa < $E_{vd}$ < 105 MPa range [60].
2) Static plate (VSS) HMP PDG Pro, manufactured by Prüfgerätebau GmbH, equipped with 1 electronic displacement sensor and a 300 mm diameter load plate.
3) VSS-3P-000 7408 static plate, manufactured by MULTISERW-Morek, equipped with 3 analogue displacement sensors and a 300 mm diameter load plate.
4) VSS-3P static plate, equipped with 3 electronic displacement sensors and a 300 mm diameter load plate.

The static plate measurements were carried out in wheel tracks in accordance with the Polish standards applicable in this area (BN-8931-02:1964 [12], PN-S-02205:1998 [9]). The important information is that the slab was loaded twice with a maximum pressure of 0.55 MPa, i.e. as for the entire road structure. The $E_1$ and $E_2$ values were therefore calculated assuming that the plate displacement Δs corresponds to the pressure differences Δp in the range of 0.25–0.35 MPa. The LWD measurements in the wheel tracks were performed according to the methodology recommended by the plate manufacturer (Zorn [61]) and IBDiM [24]. The tests were carried out at the same time as the static plate tests, with the test points placed in close proximity to the PLT test points, with a minimum distance of 1.0 m between them. During the LFWD measurements, the dynamic deformation modulus ($E_{vd}$) values and the s/v ratio were recorded. The information on the road surface structures and the geotechnical conditions of the foundation of the test sections was taken from the documentation provided by the contractor. Where necessary, it was supplemented by our own excavations and geotechnical borings. The desk work involved processing the 140 paired $E_{vd}$ and $E_2$ values, so that a PLT measurement result corresponded to the average of at least 3 LWD measurements, for each of the two drop weights used. Outliers were not removed from the database and therefore relate to the load capacity measurements taken in practise.

**Table 2.** Basic information on the test sections together with selected results of load measurements performed with static plates and a light dynamic plate

| No.[1] | Description of pavement structure, subgrade and soil conditions, ground water level[2] | $E_2$ | $I_o$ | $E_{vd}$ [$MN\cdot m^{-2}$] | | *s*/*v* [ms] | |
|---|---|---|---|---|---|---|---|
| | | | | 10 kg | 15 kg | 10 kg | 15 kg |
| Group A – unbound aggregates | | | | | | | |
| 2 | 0–1 cm crushed stone 0/8 mm, 1–13 cm crushed stone 0/31.5 mm, 13–28 cm crushed stone 0/63 mm, 28–43 cm medium sand MSa (drainage layer), 43–250 cm sandy clay saCl. | 234 | 2.1 | 75.2 | 83.0 | 2.37 | 2.37 |
| 10 | 0–1 cm crushed stone 0/8 mm, 1–13 cm natural aggregate (crushed over a minimum of 2/3 of its surface) 0/31.5 mm, 13–28 cm natural aggregate (crushed over a minimum of 2/3 of its surface) 0/63 mm, 28–250 cm fine sand with clayey sand layers FSaclsa. | 198 | 2.2 | 76.2 | 81.5 | 2.59 | 2.63 |
| 11 | 0–1 cm crushed stone 0/8 mm, 1–13 cm crushed stone 0/31.5 mm, 13–28 cm natural aggregate crushed over a minimum of 2/3 of its surface) 0/63 mm, 28–120 cm fine sand with clayey sand layers FSaclsa, 120–250 cm fine sand FSa. | 189 | 2.2 | 74.9 | 86.1 | 2.40 | 2.48 |
| Group B – bound aggregates and soils | | | | | | | |
| 3 | 0–1 cm crushed stone 0/8 mm, 1–13 cm crushed stone 0/31.5 mm, 13–28 cm subgrade cement stabilization *in situ* ($R_m$ = 2,5–5.0 $MN\cdot m^{-2}$), 28–148 cm silty sand siSa, 148–250 cm fine sand with clayey sand layers FSaclsa, 250–300 cm clayey sand clSa. | 253 | 2.3 | 75.1 | 89.6 | 2.29 | 2.33 |
| 4 | 0–1 cm crushed stone 0/8 mm, 1–13 cm crushed stone 0/31.5 mm, 13–28 cm subgrade cement stabilization *ex situ* ($R_m$ = 2.5–5.0 $MN\cdot m^{-2}$), 28-130 cm fine sand with clayey sand layers FSaclsa, 130–300 cm fine sand FSa. | 395 | 2.2 | 94.0 | 107.8 | 2.22 | 2.18 |
| 9 | 0–1 cm crushed stone 0/8 mm, 1–23 cm aggregate mix (crushed gravel 0/31.5 mm, medium sand and subsoil in proportion 10:7:5) cement (6%) stabilization *ex situ*, 23–150 cm fine sand with clayey sand layers FSaclsa, 150–250 cm fine sand with fine gravel fgrFSa. | 488 | 2.2 | 151.1 | 187.5 | 2.27 | 2.17 |
| Group C – layers with geosynthetics | | | | | | | |
| 6 | 0–1 cm crushed stone 0/8 mm, 1–13 cm crushed stone 0/31.5 mm, 13–28 cm crushed stone 0/63 mm, bidirectional geogrid (aperture size 30 × 30 mm, tensile strength MD/CMD according to PN-EN ISO 10319:2010 33/33 (-3) kN/m), 28–43 cm medium sand MSa (drainage layer), 43–250 fine sand with clayey sand layers FSaclsa. | 208 | 1.9 | 72.9 | 80.8 | 2.52 | 2.58 |
| 7 | 0–1 cm crushed stone 0/8 mm, 1–13 cm crushed stone 0/31.5 mm, 13–28 cm crushed stone 0/63 mm, polypropylene woven geotextile (tensile strength MD/CMD according to EN-ISO 10319:2010 > 23 kN/20 kN, static puncture resistance CBR according to PN-EN ISO 12236:2007 > 3.2 kN, dynamic puncture resistance according to PN-EN ISO 13433:2007 10.0 mm), 28–43 cm medium sand MSa (drainage layer), 43–140 cm fine sand with clayey sand layers FSaclsa, 140–250 cm sandy clay with fine sand FSasaCl. | 202 | 1.8 | 72.0 | 82.7 | 2.50 | 2.55 |
| 8 | 0–1 cm crushed stone 0/8 mm, 1–13 cm crushed stone 0/31.5 mm, 13–28 cm crushed stone 0/63 mm, polypropylene non-woven geotextile (weight 200 $g\cdot m^{-2}$, tensile strength MD/CMD according to EN-ISO 10319:2010 16.7 kN/18.0 kN, static puncture resistance CBR according to EN ISO 12236:2007 > 2.8 kN, dynamic puncture resistance according to PN-EN ISO 13433:2007 17.0 mm), 28–43 cm medium sand MSa (drainage layer), 43–150 cm fine sand with clayey sand layers FSaclsa, 150–250 cm fine sand with gravel fgrFSa. | 185 | 1.8 | 70.5 | 77.3 | 2.71 | 2.71 |

**Note:** 1 – number of experimental forest road section, corresponding to the series presented in diagrams (Figures 5–7), 2 – no groundwater was found down to a depth of 250 cm below ground level, $E_2$ – mean value of reloading modulus, calculated from PLT measurements [MPa], $I_o$ – mean value of the deformation index, calculated from PLT measurements [-], $E_{vd}$ – mean value of dynamic deformation modulus, calculated from LFWD measurements with a 10 and 15 kg drop weight [MPa], s/v – mean value of settlement to settlement velocity ratio, calculated from LFWD measurements with a 10 kg and 15 kg drop weight [ms].

## RESULTS AND DISCUSSION

The experiments resulted in 140-element sets of deformation modulus values (from static tests) and dynamic modulus values determined using 10 kg and 15 kg falling weights. The basic statistics on the datasets can be found in Table 3.

The modulus values obtained from the dynamic plate tests (Table 3, $E_{vd}$ rows) do not show a very high variability (coefficient of variation of about 30 %), regardless of the type of road surface structure tested. The values of the dynamic modulus obtained in the plate tests with a 10 kg drop weight (Table 3, row $E_{vd10}$) are about 10% lower than the results of the corresponding tests with a 15 kg weight (Table 3, row $E_{vd15}$). The discrepancy in the test results may be due to the different proportions of elastic and plastic deformation of the substrate at the time of the measurements with different loads, which result, for example, from the unequal compaction of the layers of road surface structures under testing.

The deformation modulus values determined in the static plate tests (Table 3, row $E_2$) vary by about 50 % more than the values determined in the dynamic plate tests. The greater variability in the results of the static plate tests is most likely due to the greater scope of influence of the static plate on the subgrade, which results in including the deformability of the deeper, unconsolidated subgrade layers in the test results. It should be borne in mind that the natural subsoil is characterized by a great heterogeneity of geotechnical parameters, resulting, for example, from the occurrence of various geological processes (e.g. glacial influence). A clear correlation ($R^2 = 0.84$) was found between the values of the dynamic modulus determined in tests carried out with a load of 10 kg and 15 kg (Figure 5):

$$E_{vd15} = 53.55 \times E_{vd10} + 242 \qquad (1)$$

The relationship (1) between the dynamic moduli obtained in the tests with the plate at different loads is most likely due to the use of the same measurement device, the consistent method of test results analysis and the zone of influence of the plate at different loads falling within the surface structure area. The linear relationship between the dynamic moduli from the tests with the plate at different loads is shown in Figure 5.

Due to the different variability of the results of the deformability tests of the subsoil made with dynamic and static plates, from the engineering perspective, there is no significant relationship between the sets of results obtained in these tests (Figures 6 and 7 for 10 kg and 15 kg loading, respectively). For a linear relationship between the sets of deformation and dynamic moduli ($E_2 = a \times E_{vd} + b$), the coefficient of determination is only about 0.5. Using other curves does not yield better results. It can therefore be concluded that the results of the dynamic plate load tests do not allow a quantitative assessment of the deformability of soil as determined by the reloading modulus.

Furthermore, for high values of moduli ($E_2$ > 300 MPa, $E_{vd10}$ > 90 MPa, $E_{vd15}$ > 100 MPa), which were mainly determined for road surfaces with hydraulically bound layers, the different variability of the results of the deformation moduli with the constant values of the dynamic modulus and the different variability of the dynamic moduli with the constant values of the deformation moduli were observed (see Figure 6, series no. 4 and 9). This situation is due to the limitations of the test device in terms of the plate settlement measurement accuracy (resolution of the measuring sensors) and it significantly limits usefulness of the results of the plate load test for the quantitative assessment of deformability of rigid pavements (i.e. hydraulically bound layers), which are characterized by low deformability.

A dynamic modulus value of not less than 54 MPa obtained in the test with a 10 kg drop weight demonstrates that an reloading modulus of not less than 109 MPa can be achieved (Table

**Table 3.** Basic statistics on the data sets of the soil deformation tests

| Modulus values | n | Min | Max | Mean | SD | Cv |
|---|---|---|---|---|---|---|
| | [-] | [MPa] | [MPa] | [MPa] | [MPa] | [-] |
| $E_{vd10}$ | 140 | 54.3 | 189.7 | 81.0 | 21.4 | 0.26 |
| $E_{vd15}$ | 140 | 64.1 | 249.8 | 92.4 | 29.3 | 0.32 |
| $E_2$ | 140 | 108.9 | 750.0 | 248.6 | 112.8 | 0.45 |

**Note:** Min – minimum value, Max – maximum value, SD – standard deviation, Cv – coefficient of variation.

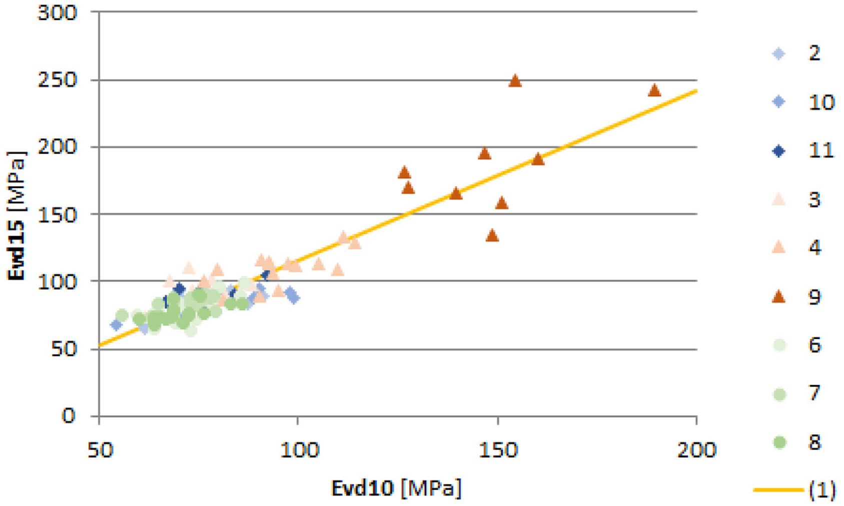

**Figure 5.** Relationship between the dynamic moduli from the plate tests with a 10 kg ($E_{vd10}$) and a 15 kg ($E_{vd15}$) drop weight

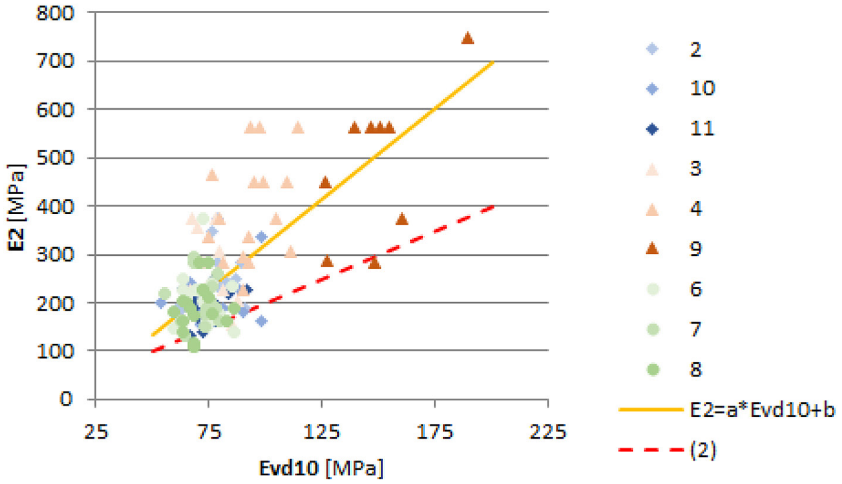

**Figure 6.** Relationship between the dynamic moduli from the plate tests with a 10 kg drop weight ($E_{vd10}$) and the reloading moduli from the static plate tests ($E_2$)

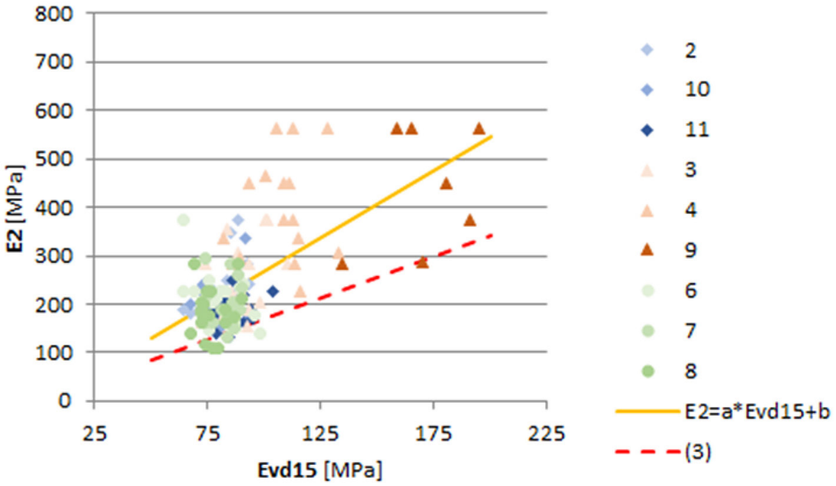

**Figure 7.** Relationship between the dynamic moduli from the plate tests with a 15 kg drop weight ($E_{vd15}$) and the reloading moduli from static plate tests ($E_2$)

3, minimum values). From the above values, a commonly used simple relationship between the values of the dynamic modulus and the reloading modulus is obtained [37, 43–46], which is also shown in Figure 6:

$$E_2 = 2.0 \times E_{vd10} \tag{2}$$

Out of the 140 elements analysed for the different surface structures tested with a dynamic plate with a 10 kg drop weight, in only 10 cases (approx. 7%) were the results of the static plate tests below these resulting from the relationship (2). In these 10 cases, the average underestimation of the reloading modulus was only 14% and the maximum underestimation of the reloading modulus did not exceed 25%.

The achievement of a dynamic modulus of not less than 64 MPa as a result of plate load tests with a 15 kg drop weight indicates the possibility of achieving an reloading modulus of not less than 109 MPa (Table 3, minimum values). Based on the above and the proven clear relationship between the dynamic modulus values obtained from tests with different weights (Figure 5), an analogous simple relationship can be formulated between the modulus values from dynamic plate tests with a 15 kg drop weight and reloading moduli from static plate tests.

$$E_2 = 1.7 \times E_{vd15} \tag{3}$$

In the analysed set of 140 results for tests on different surface structures using a dynamic plate with a drop weight of 15 kg, only in 8 cases (approx. 6%) were the results of tests with a static plate below these resulting from relation (3). In these 8 cases, the average underestimation of the reloading modulus was only 12% and the maximum underestimation of the reloading modulus was no more than 24%. Relationships (2) and (3) can be used for the qualitative evaluation of the road works and effectiveness of the forest road surfacing structures used, by utilising the results of the dynamic plate tests and the requirements defined by the reloading moduli. The effectiveness of this type of evaluation depends on the way in which the dynamic plate tests are carried out. It is recommended to perform at least 3 series of dynamic modulus measurements to determine the reloading modulus from their average value.

## CONCLUSIONS

Based on the deformation tests carried out with static and dynamic loading on different forest road surfaces, the following conclusions can be drawn:

1. There is a clear correlation between the results of the tests carried out with the dynamic plate using different loads (10 kg and 15 kg).
2. The results of the tests with the dynamic plate do not allow a quantitative evaluation of the deformability of subgrade, which is determined by the reloading modulus.
3. To quantify subgrade deformability with a dynamic plate, acceptance requirements which take into account values of the dynamic modulus must be developed.
4. The results of testing the road subgrade behaviour with a dynamic plate allow a qualitative assessment of the deformability of the ground, which is determined by the reloading modulus.
5. Simplified relationships between the values of the dynamic modulus and the reloading modulus are approximate and can only be used for the ongoing monitoring of the works and the assessment of its quality.

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