JOURNAL OF FOREST SCIENCE, *56*, 2010 (3): 130–136

Possibilities of using the portable falling weight deflectometer to measure the bearing capacity and compaction of forest soils

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ABSTRACT: The paper discusses possibilities of using the portable falling weight deflectometer to measure the bearing capacity and compaction of forest soils. Within the study, measurements were made using manual penetrometer and Loadman II portable falling weight deflectometer. To eliminate the extreme values, Grubbs's test was used. The results indicate that Loadman II deflectometer may be used to measure both the bearing capacity and compaction of forest soils under the canopy as well as in transport lines. A significant difference was found between deflection of water-unaffected sites and water-affected sites (12.08 and 2.31 mm, respectively). Measurements of bearing capacity after removal of forest litter give far more precise details; however, the authors do not refuse the measurements without litter removal, either. To determine the degrees of soil compaction, it is useful to measure the soil reaction time; to measure the bearing capacity it is vital to measure deflection.

Keywords: deflection; E-module; PFWD; soil bearing capacity; soil compaction; soil reaction

The moto-manual technology of wood production is often replaced by fully mechanized technologies. The degree of mechanization is gradually increasing and the timber harvesting and hauling machines do the processing of an ever-higher percentage of annual prescribed cut in the Czech Republic. The timber logging and hauling machines are mainly farm tractors, harvesters and forwarders (wheeled, trucked and/or combined) in the Czech Republic. However, the use of these technologies also entails soil damage hazards. The most frequently occurring reasons for damage to forest ecosystems may be improper machine design, choice of inappropriate technology or year season for the concerned site, technological or work indiscipline or failure in mastering the given technology. Even if we observe all basic rules for the employment of machinery, we cannot avoid some soil damage (even if minimal) because the machine (even if properly used) affects negatively the soil by travelling thereupon. We can observe the greatest soil compaction (increased density) immediately after the first machine pass after which the soil density increases relatively steeply until the fifth pass and then does not show any other marked change (Simanov, personal communication). Soils damaged in this way return only very hardly to their original condition.

Soil compaction entails the diminishing pore size. Šály (1978) claims the average pore size being equal to 0.3–0.7 μm of the earth particle diameter. Pores of diameter lesser than 0.2 μm fix water very tightly and are as a rule filled with it. Pores under 0.01 mm are not available to root hairs and pores under 0.001 mm are not inhabitable even by micro-

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Supported by the Ministry of Education, Youth and Sports of the Czech Republic, Project No. MSM 6215648902, and by the Ministry of Agriculture of the Czech Republic, Project No. QH71159.

organisms. The compaction of forest soils increases the bulk soil density and if it exceeds the boundary of 1.8 g.cm^{-3}, the penetration of roots ceases to occur (Demko 1994), which is in accordance with the finding that soil compaction leads to changes in the growth of roots.

The compaction of soils closely relates to the formation of ruts that later develop into water-bars and initial places for the formation of erosion rills if the transport line is led improperly. The risk of water erosion also connects with sod stripping by skid timber or by the lower frames of machines. The risk of water erosion after the previous sod stripping due to the insufficient adhesion of skidding mechanism wheels is clearly evident at a slope angle of 33% (Simanov, personal communication).

The impact of machine travel on soils (especially fine-textured ones) started to be studied some 20 years ago and results of these studies are generally known. The employment of harvesters and forwarders entails a risk of soil disturbance namely on water-logged, clay soils in which the passing machines disturb the soil structure by compressing large pores. In general, the compression of pores unfavourably affects the soil structure, gas exchange and water movement in both horizontal and vertical direction. Uncontrolled soil erosion occurs on hill slopes. The machine affects the soil by its weight, i.e. by static pressure, but also by dynamic effects (impacts) that may be far more dangerous in terms of soil disturbance.

Šach (1988, 1990), Šach and Černohous (2009) presented risks and methodological procedures for the estimation of forest soil damage by erosion and for the protection of forest soils against erosion due to logging and hauling activities. One of the criteria considerably affecting erosion is the bearing capacity of soil. The bearing capacity of soil can be explained in other words as the capacity of soil to sustain load. By means of this variable, we can determine what machines are acceptable in the given environment with respect to soil disturbance. Nevertheless, the bearing capacity of soil will not prevent the soil from compaction. The degree of compaction (toughness) can be established by means of deflectometers. However, deflectometers are primarily designed to detect the quality of road base structures. Their advantage consists in the fact that they are non-destructive and capable of measuring lower layers of the roadbed.

Compared to conventional (large) falling weight deflectors the portable (smaller) deflectometers were designed for convenient handling. Another reason for introducing portable deflectometers and their advantage as compared with the conventional ones is a markedly lower purchasing and operation cost. In terms of applicability in the measuring of forest soils, we can only consider the use of portable deflectometers because the large conventional ones cannot be properly moved within the stand. Holtz and Kovacs (1981) inform that portable falling weight deflectometers (PFWD) are light devices developed for the purpose of measuring the rigidity of road body structural layers including sub-base layers. The falling weight induces a non-destructive shock wave spreading in the soil, which evokes the reaction according to actual soil properties. The difference of reaction is measured with velocity pick-ups and with sensors measuring the accelerated reaction of the surface (accelerometers). The first model of PFWD Prima 100 was developed in Denmark by Keros Technology. It was equipped with exchangeable weights of 10, 15 and 20 kg and with three exchangeable base plates of 100, 200 and 300 mm in diameter.

The next type of PFWD was Loadman, which was developed by Al-Engineering Oy in Finland. This deflectometer is today used by more than 60 research organizations, universities and research workplaces in Canada, Estonia, Finland, India, Israel, Italy, Pakistan, Russia, Sweden, etc. Its variability is not as high as that of Prima 100 because it has a standard weight of 10 kg, reaction base plates of 132 and 300 mm in diameter and a standard falling weight height of 800 mm. Its maximum dynamic load is about 23 kN.

As compared to conventional deflectometers, the portable models are due to their tiny design susceptible to the influence of many factors distorting the measurement. Steinert et al. (2005) compared common conventional deflectometers with portable models in respect of their mutual correlation in terms of measurement accuracy. In comparing the portable and conventional deflectometer, correlation coefficients ranged in general from 0.50 to 0.86 with the portable deflectometers generally showing higher module values. Including optimum moisture content in the factors of field measurements, Steinert et al. (2005) found out that if the optimum moisture content of the carriageway drops by 4%, the module of elasticity might be affected up to 31 MPa.

Whaley (1994) compared the conventional deflectometer with the Loadman and concluded that the measurement with PFWD is not so accurate as the measurement with conventional deflectometer while measured values are higher and correlation coefficient is markedly lower. He explains the low correlation by the portable deflectometer having lower weight and shock waves therefore penetrating only into the upper soil layers. Comparing the two deflectometers he arrived at a correlation coefficient of 0.78. The solution to this problem in literature suggests that when a greater number of measurements is taken and the extreme values are excluded, it is possible to reach a higher correlation coefficient.

Comparing the Loadman and the common conventional deflectometers, Pidwerbesky (1997) arrived at the following regression equation:

$$y = 1.06x + 10 \qquad (1)$$

where:

x – Loadman values of elasticity module in MPa,

y – elasticity module values of conventional deflectometers.

The correlation coefficient was 0.5132 in this case but the author unambiguously claims that using a PFWD is a much faster method enabling to enlarge the tested area as well as the frequency of measurements. Loadman also facilitates an easier handling of the instrument and an easier interpretation of measuring results and it does not need calibration for each type of material.

Lin et al. (2006) studied factors affecting the measurement with portable deflectometers and pointed out that a correct choice of the reaction base plate is of vital importance. They concluded that portable deflectometers are the right choice to measure the compaction of individual road base structures from many aspects, namely due to their easy handling and expeditious data acquisition.

Miller et al. (2007) analyzed the depth to which stress effects can be detected. They established that the stress in lightweight PFWD (stress effect) could be measured at a depth which is 1 to 1.5 times the base plate diameter.

The application of PFWD for measuring the compaction of transport lines or forest soils has *de facto* never been published. Only Haarlaa et al. (2001) reported in his paper that a deflectometer was used for the measuring of transport lines on peat soils in Finland and recommended to use a base plate of 300 mm in diameter and to measure soils without the A horizon – with the denudated humus layer. He also pointed out that it was useful to carry out a minimum of two to three measurements at each site.

The goal of the present paper was to assess a possibility of using the portable falling weight deflectometer for measuring the bearing capacity and compaction of forest soils. The comparative measuring instrument was a lightweight manual penetrometer that had been used for measuring the bearing capacity of forest soils in many cases.

MATERIAL AND METHODS

The measurement was made by using portable falling weight deflectometer Loadman II USB and Eijkelkamp manual penetrometer. The work procedure of measuring with penetrometer presented by Matys et al. (1990) was modified for manual penetrometer. Soil bearing capacity was measured by using a cone type with 3.3 cm^2 cone base area and 60° top angle. The values of soil resistance to the penetrating point were measured with the pressure gauge (instrument part). The penetration rate was ca 2 cm per second – with equal pressure exerted onto both handles.

The measuring with deflectometer was conducted in two modes: at first, deflection values were measured 7 times at the same place where the humus layer was not removed; then the measurement was made twice at the same place with the removed humus layer. The measurements were taken in various parts of the forest stand so that values could be recorded on slightly elevated sites (unaffected by water), on water-affected sites, and on the transport line.

Firstly we removed all objects that could affect the behaviour and results of the measurements (stones, branches). Then the instrument was placed at a vertical position and its base was (if necessary) levelled by twisting so that the entire instrument area was properly seated on the soil. Prior to the first measurement, the instrument was calibrated according to the size of the reaction base plate. The diameter of the reaction base plate was 132 mm and the calibration module of elasticity was chosen to be E 160 as advised by the manufacturer. (*Note: This value was determined by the manufacturer to be a value with the highest correlation towards conventional deflectometers.*) During the measurement, the instrument was subtly held in vertical position at all times so that the measurement could not be affected by the grip. In cases with the removed litter, it was necessary to assure a full seating of the instrument on the ground surface by twisting movements.

All measurement results were stored in the instrument's memory under different locality identifications.

The sample plot where the measurements were taken was subsequently subjected to the soil sampling by means of physical Kopecky metal rings in order to detect the actual soil moisture content. A soil pit was excavated on the plot into a depth of 30 cm. In this soil pit, we levelled the walls to a flat vertical position and took a sample of mineral soil by using physical Kopecky metal rings. Wet soil samples were weighed in laboratory conditions with the accuracy of grams and inserted into an oven where they were dried at a temperature of 103°C (+/–2°C) for 17 hours. Then the soil samples were weighed in dry condition and moisture contents of soils in the individual sites were calculated.

Gross errors were eliminated from values measured with the penetrometer and deflectometer by using Grubbs' test of gross errors (Sachs 1984) and the following calculations:

$$T_{\min} = \frac{\bar{x} - x_{\min}}{\sigma} \qquad (2)$$

$$T_{\max} = \frac{x_{\min} - \bar{x}}{\sigma} \qquad (3)$$

where:
$\bar{x}$ – mean value,
$x_{\max}$ – maximum value,
$x_{\min}$ – minimum value,
σ – standard deviation.

If a $T_{\max}$ or $T_{\min}$ value exceeded the critical value for Grubbs' test at a corresponding degree of freedom and significance of 0.05 at a level of accuracy +/–5%, it was established as a gross error. If such an error occurred, it was eliminated from the data file and the entire test was repeated.

Programme Curve Expert 1.3 was used to determine the most appropriate and most accurate correlation.

RESULTS

Forest stand 146 D 8 and its characteristics were as follows:
Area: 26.49 ha
Tree species representation: spruce 61%, larch 21%, pine 17%, fir 1%
Forest type: 4K5
Primary management group of stands: 421
Spruce and larch – certified stand of phenotype category B
Haplic Albeluvisol LUm with distinctly developed, deep horizons and a fully developed humus sub-form of typical moder. So-called absolute soil depth – D-horizon in the form of compact rock.
Site characterization: very mild gradient 3°, eastern aspect

Soil profile characterization (Buchar 2009):

0–1	L	relatively fresh spruce litter
1–2	F	partly decomposed spruce litter
2–4	H	distinct signs of advanced decomposition and subsequent humification, without recognizable structure
4–9	A	10YR 2/1, strongly humic, loamy, loose, slightly moist, with high porosity and medium biological activity, dense rooting
9–33	El	10YR 7.5/6, bleached, scaled structure, easily decomposing, mildly moist, with high porosity and indistinct rooting
33–55	EB	5YR 5/8, sandy-loamy, moist, with medium porosity and indistinct rooting
55–75	Bt	5YR 4/6, loam to clay-loam, moist, without mottle, packed
75 →	D	compact Devonian limestone.

The curves of penetration resistance at depths from 5 to 35 cm are presented in Fig. 1. The curve of penetration resistance from the transport line of the water-affected site was extremely high. A subsequent inquiry revealed that the transport line was renovated in the past, which resulted in entirely different soil penetration resistance values. The curves of soil resistance are regression equations of the measured values, which were as follows:

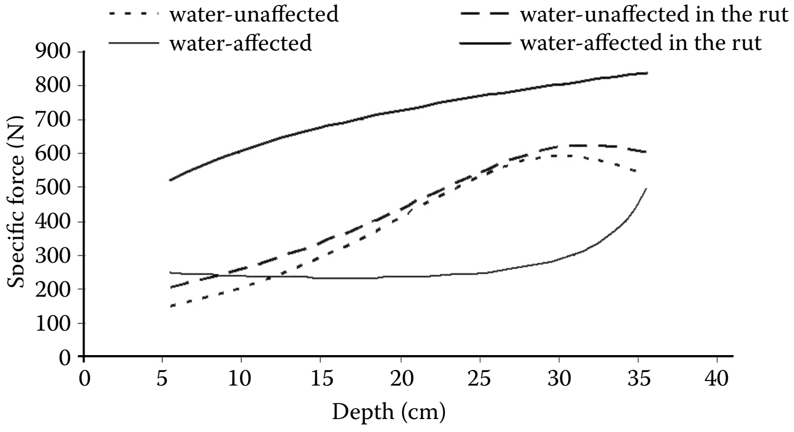

Fig. 1. Curves of soil penetration resistance

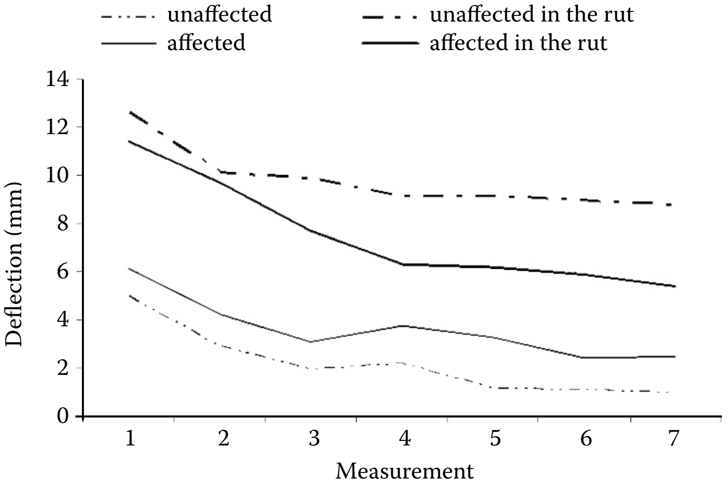

Fig. 2. Multiple deflection measurement on sites with litter

$$y = \frac{108.369 + 1.0934x}{1 - 0.0531x + 0.000923x^2} \tag{4}$$

for water-unaffected sites (standard deviation 0.886):

$$y = \frac{164.223 + 0.550x}{1 - 0.0477x + 0.000744x^2} \tag{5}$$

for water-unaffected sites at the transport line (standard deviation 0.818):

$$y = \frac{260.260 + 5.406x}{1 - 0.00893x - 0.000444x^2} \tag{6}$$

for water-affected sites (standard deviation 0.646):

$$y = 352.504x^{0.243} \tag{7}$$

for water-affected sites at the transport line (standard deviation 0.435).

A multiple measurement on one site with litter is illustrated in Fig. 2. The measured values have a decreasing trend and at the seventh measurement they reach approximately a half value of the initial measurement. Deflection in the transport line rut is at all times higher than deflection measured outside the transport line in both cases, i.e. on sites unaffected by water and on water-affected sites.

Multiple measurements on one site without litter are illustrated in Fig 3. The measured values do not show any distinct changes. Deflection in the transport line rut is at all times higher than deflection measured outside the transport line in both cases, i.e. on sites unaffected by water and on water-affected sites.

The results of measurements on different sites within the forest stand after the removal of litter are shown in Fig. 4. The left side of the diagram contains values measured on water-unaffected sites and the right side of the diagram contains values measured on water-affected sites. Average deflection on water-unaffected and water-affected sites was 12.08 mm and 2.31 mm, respectively.

DISCUSSION

The measuring of deflection without litter removal showed considerably unbalanced results with a de-

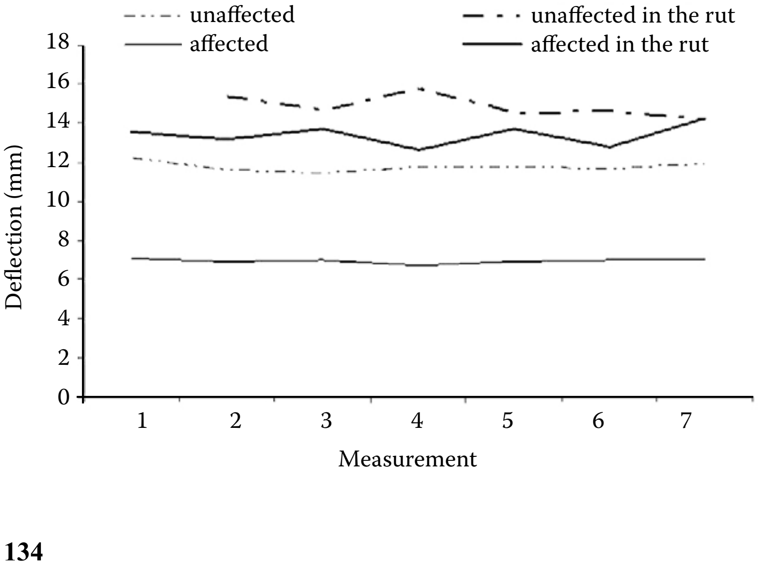

Fig. 3. Multiple deflection measurement on sites after litter removal

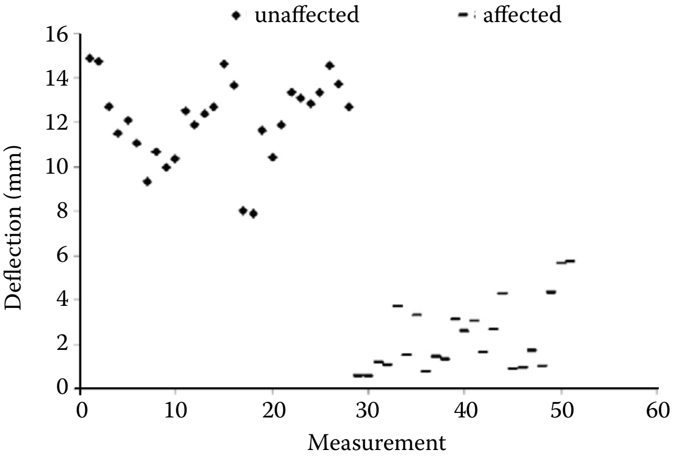

Fig. 4. Deflection measured on different sites within the stand after litter removal

creasing trend on all four sites. This is presumably caused by the properties of litter (surface layer) changing due to the falling weight. Litter thickness was approximately 4 cm, and if the capacity of deflectometer is to measure into a depth of ca 1.5 multiple of reaction area (Miller et al. 2007) it is very significant with respect to the measured profile. Nevertheless, the authors do not condemn the measurement with litter. Harvesters pass through the forest stand usually only once and litter can markedly affect the total bearing capacity of soil. The measurement without litter appears to provide a more accurate determination of soil bearing capacity.

The measurement of soil bearing capacity after litter removal outside the transport line and on the transport line shows apparent differences. The soil that is compacted or has a higher bearing capacity reacts more readily to the weight which acquires higher energy after the fall, i.e. higher deflection. Water-affected sites (less compacted soils with lower bearing capacity) readily absorb the energy and the measure of deflection is therefore lower.

If we compare the measurement with penetrometer and deflectometer, we can follow the degree of soil bearing capacity in the following order (from the most bearing/compacted ones):

- measured with penetrometer: water-affected sites on the transport line, water-unaffected sites on the transport line, water-unaffected sites outside the transport line, water-affected sites outside the transport line;
- measured with deflectometer: water-unaffected sites on the transport line, water-affected sites on the transport line, water-unaffected sites outside the transport line, water-affected sites outside the transport line.

The authors maintain that the penetrometer measurements are distorted due to the previous transport line renovation but in terms of the soil bearing capacity, a more important role will be that of water-affection. This transport line was by sight less bearing than the transport line on the water-unaffected site although the soil moisture content amounted to 19% at the multiple measurement without litter as well as with litter on the water-unaffected site while on the water-affected site it was 19.6%.

As to the identification of compaction and establishment of compaction degree, the authors maintain that acceleration (soil reaction time) can also be used. In the transport lines, the soil reaction time was markedly shorter and ranged in the order of half-reaction times of non-compacted soil.

All these theories lead the authors to a further and more in-depth exploration after which it would be possible to express a hypothesis that the degree of soil bearing capacity can be established in dependence on soil moisture content and that soil reaction time depends on soil compaction.

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Received for publication June 17, 2009
Accepted after corrections August 10, 2009

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