Measuring the Bearing Capacity of Forest Roads with an Improved Benkelman Beam Apparatus

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Abstract – Bearing capacity measurements of roads were traditionally carried out using the Benkelman beam. The Benkelman beam measurements provide the maximum vertical deflection of the pavement under 50 kN of wheel load. Nowadays the bearing capacity of public roads is measured with falling weight deflectometers. Falling weight deflectometer measurements provide the full deflection basin. It is convenient to use these high precision instruments on forest roads, but their application is inefficient and costly. The Department of Forest Opening Up developed a new method to measure the full deflection basin with the Benkelman beam. Besides the instrument improvement the authors developed a new method for the processing of the deflection basin data. Results are presented through the case study of a 2nd class opening up forest road.

Benkelman-beam / forest road / bearing capacity / pavement management system

Kivonat – Erdei utak teherbírásának mérése a Benkelman-gerenda továbbfejlesztett változatával. Az erdészeti szállításban mértékadónak tekinthető tehergépjármű állomány az elmúlt évtizedekben nagy tengelyterhelésű járművekre cserélődött le; ez a folyamat a szállítópályák leromlását felgyorsította. Mindezek miatt az erdőfeltárás témakörében a hangsúly a feltáróhálózatok bővítéséről áthelyeződött a meglévő utak fenntartására és fejlesztésére. Az Erdőfeltárási Tanszéken folyó kutatások – az erdőgazdaságok által megrendelt kutatás-fejlesztési megbízásokkal párhuzamosan – követik ezt a trendet; a cikk az aszfalt kopóréteggel rendelkező pályaszerkezetek teherbírásának roncsolásmentes meghatározása területén elért legújabb eredményeket mutatja be.

Benkelman-gerenda / behajlásmérés/ erdészeti utak teherbírása / útfenntartási rendszer

1 INTRODUCTION

One of the most important, objectively measurable parameters of the road maintenance systems is the bearing capacity of the roads. To define the bearing capacity of the elastic pavements is not an exact task, as we do not have a widely accepted theory to do this. In addition, we can state, that the definition of the bearing capacity of pavements is also difficult. Unlike bearing capacity, stiffness – as the deformation caused by a given weight – can be

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defined, and even measured. Instead of defining bearing capacity directly, we usually look for the answers to these questions:

- How long is the remaining lifetime of the pavement?
- Which recovering technology should be used based on the bearing capacity and surface condition of the pavement?
- How thick the stiffening layer covering the pavement should be, to endure the next 10–20 years of traffic?

The study describes development results achieved at the Forest Opening Up Department of the University of West Hungary, through which the deformation of elastic pavements caused by weight can be measured. The advantage of the method is that the whole deflection bowl can be measured applying a low cost equipment.

2   MEASURING THE DEFORMATION OF PAVEMENTS

During the last decades several procedures have been developed to measure the deformations of elastic pavements. Each procedure simulates the relationship between the traffic and the pavement differently. Because of this, the measured results vary slightly. We briefly present the methods that have been used in forestry practice so far. The *Table 1* contains the main features of the measurement tools (Kosztka et al., 2008).

Table 1.   Comparison of deflectometers.

Features	Benkelman beam	Lacroix deflectograph	FWD
Tools needed	loaded truck 2 pcs Benkelman beam	measuring vehicle	measuring vehicle
Staff	4 pers.	2 pers.	2 pers.
Stress	static	actually static	dynamic
Simulated speed	0 km/h	3-4 km/h	60-80 km/h
Method of measurement	discrete	permanent	discrete
Frequency of measurement	min. 25 m	4 m	25 m
Daily performance	15 km	20 km	15 km
Measured parameter	central deflection	central deflection	deflection bowl
Data recording	manual	automatic	automatic
Repeatability	satisfactory	average	excellent
Cost of tool	cheap	expensive	expensive

The classic tool to measure deflections is the *Benkelman beam*. During the measurement a rod that stands against the pavement and spins round a horizontal axis is placed between the rear dual tires of a loaded truck at the place of the maximum deflection. The deflection of the pavement can be defined from the displacement measured at the other end of the rod. During the measuring process the truck stands still, so the weight is static (Boromissza 1959).

We can apply the Lacroix Deflectograph to automatically measure the deflections. The principle of this measurement is the same as the principle of the manual method. The difference is in the implementation. Here the deflétion meters are fixed to an automatic measuring vehicle, which measures the pavement's deflection every 4 meters while slowly (3–5 km/h) progresses. The deflection measurement technique made by the

Lacroix Deflectograph has not spread in forestry practice because of its circumstantiality and high cost. On the other hand, the former researches at the Forest Opening Up Department showed, that as to the renewal plans of forestry roads, the manual deflection measurement method, which needs simpler tools, leads to the same results (Boromissza 1959, Kosztka et al. 2008).

The public road practice uses the Falling Weight Deflectometer (FWD) to measure the deformations of elastic pavements – that is the deflection bowl – caused by load. The FWD devices, at several points at once, precisely measure the vertical displacement caused by dynamic load with the help of accelerometer sensors placed on the pavement surface. The device measures the temperature of the air and the pavement too. The adaptation studies to establish the application of the dynamic bearing capacity measurement in Hungary began in 1991. According to these, we can state, that the measurement procedure is rapid and objective (Tóth 2007). The measurement technique – according to our experiences of the last years – can be applied successfully in forestry conditions (Kosztka et al. 2008).

3 THE POSSIBILITIES OF DEVELOPING THE MANUAL DEFLECTION MEASUREMENT METHOD

Using the FWD device we can measure the deformations of the pavement surface at several points beside the central deflection, so the shape of the deflection line (deflection bowl) can also be produced. Knowing the shape of the deflection bowl we can estimate parameters that are the input data of pavement design procedures based on mechanical principles. We believe that we should prefer the measurement procedures that make the whole deflection bowl be possible to record. The price and maintenance cost of the Falling Weight Deflectometers are very high, so the bearing capacity measurements on forestry roads can only be carried out by specialist companies that own FWD devices. It seems practical to develop a procedure that enables specialists dealing with forestry roads to independently measure the deflection bowl.

4 THE GEOBEAM AND OTHERS

The Geobeam is an automated Benkelman beam, the development of which began in the 1980's (Tonkin &Taylor). The main purpose of the development was to preserve the simple principle of the manual deflection measurement method while automatically recording the whole deformation line, with little expense increase. During the measurement the sensor of the measuring beam automatically records the vertical displacement while assigns the load position to the measurement. So the deflection bowl can be reconstructed by the appropriate processing software. The position of the load is measured and recorded with the measuring wheel attached to the truck. The resolution of the measuring wheel is 10 mm, which enables very frequent sampling. Unlike the FWD device, the Geobeam records the vertical displacement of a point at different times (Anderson, 2008). The measurement system is shown in *Figure 1*.

The Geobeam provides usable, representative measurement results even in cases when because of the saturated foundation, the FWD tools cannot be reliably applied (consolidation issue) (Anderson, 2008).

Figure 1. The Geobeam measuring equipment (Geotechnics Ltd.)

Naturally, there are several other solutions to improve the manual deflection measurement method beside Geobeam. It is worth mentioning the manual deflectometer applied at the Faculty of Civil Engineering, Bauhaus-Universität in Weimar. This method applies three more sensors beside the central sensor at 25-50-80 cm from the axis of load. The displacements recorded by the sensors are processed and stored automatically by the electronic device fixed onto the measuring beam. This method, just like the FWD tools, records the displacements at different discreet points (4 measured points). With the help of the function fitted to the measured values, different bowl parameters can be computed (Dähnert, 2005). This equipment is shown in *Figure 2.*

Figure 2. Automated Benkelman beam (Dähnert, 2005)

5   THE IMPROVED BENKELMAN BEAM APPARATUS

The procedure developed at the Forest Opening Up Department was the result of the improvement of the manual deflection measure method. The development included planning the measurement process, choosing the necessary accessory equipment, designing and building the central data collecting unit, developing the firmware running on the data collecting hardware and the data collecting and analyzing software running on PC-s.

The development in respect of the equipment basically lies on three pillars:
1. We substituted the traditional Benkelman beams' analogue meters with meters having digital output.
2. During the measurement we record the progress of the truck with an ultrasonic rangefinder.
3. The signal of the digital sensors is recorded then transferred to the netbook that runs the data collector software, using a self-developed central control unit.
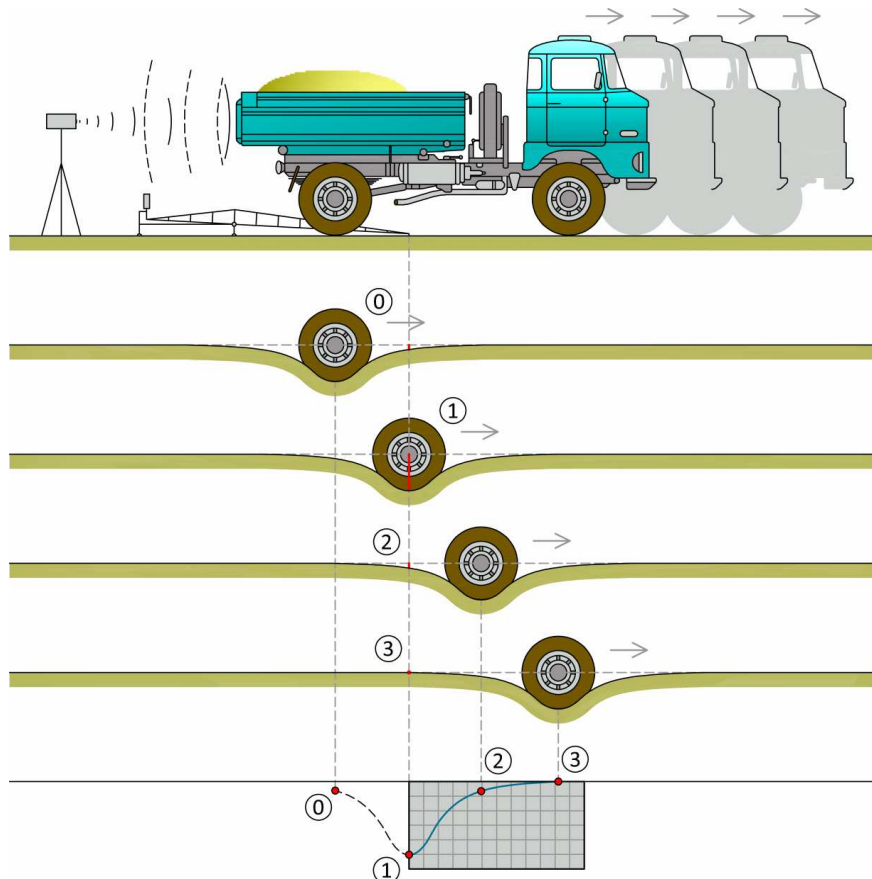

Figure 3. The principle of the improved manual deflection measurement method

The measurement procedure consists of the following steps *(Figure 3)*:
1. Driving a loaded truck with known rear axle load to the segment of the measurement.
2. Placing deflectometers between the dual tires of the rear axle so the measure peak will be in front of the contact line of the wheel.
3. Positioning the digital displacement meters.
4. Positioning the ultrasonic rangefinder placed on a stand.
5. Preparing the data-collector touch-screen netbook to receive the measurement data, checking the data connection with the external hardware.
6. Starting data collection with the data collector software.
7. While the truck slowly drives away, the data collector software records the data of the digital meters and rangefinder sensor.
8. After progressing 5 m ahead, the data collection stops automatically.

The measuring device records the vertical displacement of one point of the pavement by assigning the loading distance to every "reading" of the displacement meters. After properly pre-processing the data flow the shape of the deflection bowl can be drawn.

6   HARDWARE COMPONENTS

We took the following aspects into consideration when we chose the type of digital meter fixed on the Benkelman beam:
- At least 0.01 mm resolution.
- At least 10 Hz measurement frequency.
- At least 25 mm measurement range.
- Open format digital data output.
- Robust design for outdoor measurements.
- The beam is the same diameter (8 mm) as our analogue meters.
- Reasonable price.

After studying the market choice, we chose the type ID-U meter of the Mitutoyo Company. Mitutoyo is one of the leader manufacturers of precision measurement equipment, and the ID-U meter completely meets our requirements listed above. The meter has digital data output, the enclosed data cables have standard connectors by which the equipment can be connected to data collectors manufactured by the company or developed in-house. The DIGIMATIC digital data-exchange format developed by Mitutoyo is well documented and simple. The hardware realization of the communication – logical signal levels, timing, external controllability etc. – enables the sensor to fit in a self-developed microcontroller environment. We record the progress of the truck with a type SRF-08 ultrasonic rangefinder sensor. The main features of the sensor:
- 1 cm resolution.
- 30 cm – 6 m measurement range.
- High sampling frequency (> 20 Hz).
- I_2C standard communication.
- Low price.

The sensor was built in the central data collecting unit's box mentioned later. The central data collecting and control unit is built around a type Microchip 18F2550 microcontroller. The tasks of the instrument group's "brain":
- Connection through a USB HID standard communication protocol, data exchange with the data collecting software running on a PC.
- Synchronized start of the digital displacement meters' and rangefinder sensor's measurements with the frequency of 10 measurements per second.
- Receiving and converting the measurements of the sensors.
- Transferring the results to the data collector software.

The data collector control unit is powered from the PC's USB port. The microcontroller and the components built around it are placed on a self-designed and manufactured printed-circuit. We wrote the program (firmware) run on the microcontroller with the education version of the Microchip MPLAB developer tool, in C language. We placed the control unit in a plastic box, which can be fixed onto a camera stand by a fast connector. The data collecting software is run on a type Vye touch screen netbook. The data collector control unit is shown in *Figure 4*, while the assembled instrument group is shown in *Figure 5*.
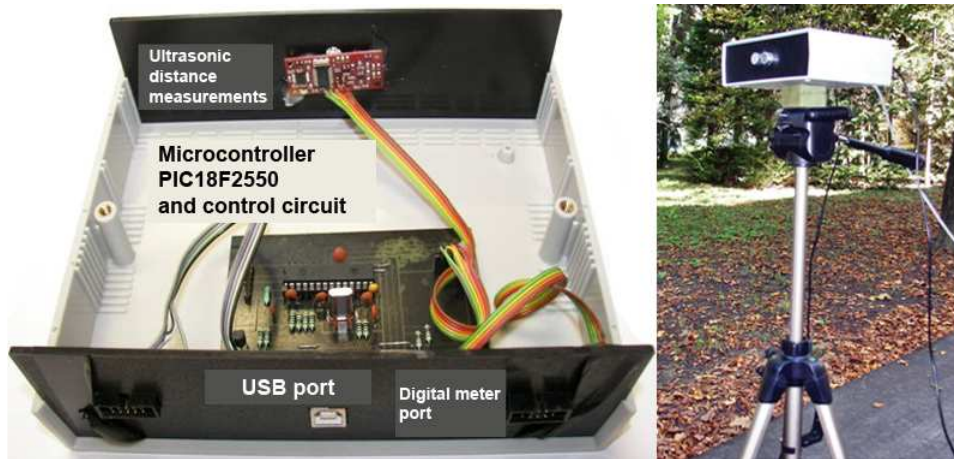
Figure 4. The central data logging unit.

Figure 5. The instrument group in use.

7   SOFTWARE COMPONENTS

During fieldwork the software run on the netbook supports the control, pre-process of the measured data and storage of the measured results. The software written to support the office process of the measurement results provides the following functions:
- Equalization of the measured data series.
- Numerical definition of the function corresponding the mechanical calculi, appropriately describing the shape of the deflection bowl.
- Defining the parameters (length of the deflection bowl, the location of the inflexion point, minimum curve radius, central deformation, shape factor) typical of the shape of the deflection bowl and bearing capacity with the help of the fitted functions.

8   PRE-PROCESS OF THE MEASUREMENT RESULTS

After the general description of the manual deflectometer developed at the Forest Opening Up Department it is practical to review the features of the recorded data series. During the measurement the data collector software records the displacements (d) read by the digital meters, records the momentary distance of the wheel load (x), and the elapsed time (t) from the start of the measurement. The shape of the detected deflection bowl is clearly defined by the function $f : x \rightarrow d$ *(Figure 6)*.
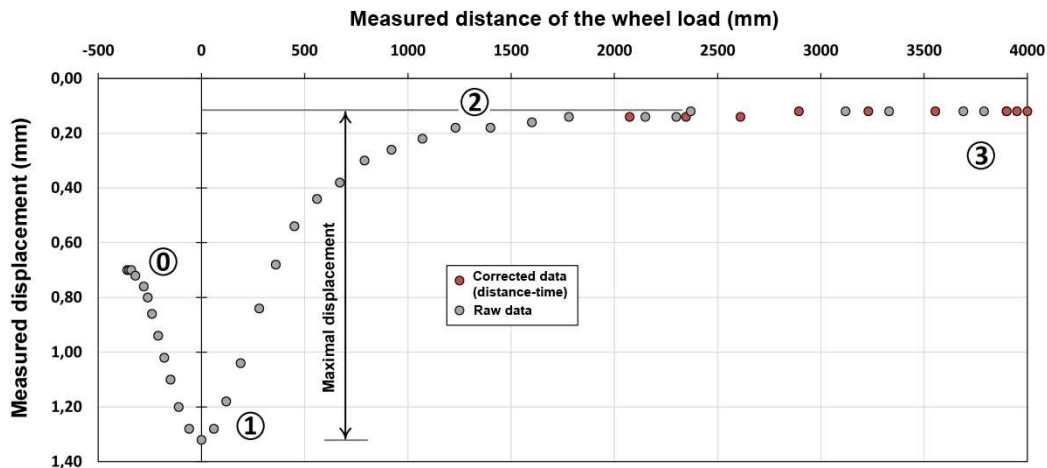

Figure 6. Measured points of the deflection bowl.
Red dots represent corrected measurements

On the raw data series it can clearly be seen, that during the measurement the peak of the deflectometer is placed 40-50 cm in front of the wheel contact point. During the first stage of the measurement the pavement structure suffers a gradually increasing shape deformation (0–1) then when it passes the measuring peak, the deformation reaches its maximum (1). As the wheel passes the measuring peak, the pavement structure gradually gains its original shape (2–3). The deformation line can be recorded by the measurement equipment in 5 m length.

As to the raw data, we can also observe, that they more or less vary along a definite trend, so they are charged with noise. Both members of the data pairs (x, d) describing the deflection bowl are charged with measurement error, the rate of which depends on the features of the sensor that recorded the given parameter. Out of the three recorded parameters the most reliable one is the time (t), next is the displacement (d), and the last one is the position of the moving wheel load (x). We practically start the noise reduction with observing the x parameter. The distance-time diagram is the graphic image of the distance covered by the wheel load versus time *(Figure 7)*. We can follow the acceleration of the moving wheel load. The entire load time period is approx. 3 seconds, so the wheel-speed is an average of 5 km/h. This value is similar to the measurement speed of the Lacroix Deflectometers that is why the measurement is not static, but static-like. We can also observe, that the last 5-10 recorded values of the ultrasonic rangefinder (red bordered area) are charged with errors, so they are worth being substituted with a regression function fitted onto the whole measured data-series or with a spline curve. Using this method, we can relatively reliably reduce the number of errors from distance measurement (see the corrected values of *Figure 6*).
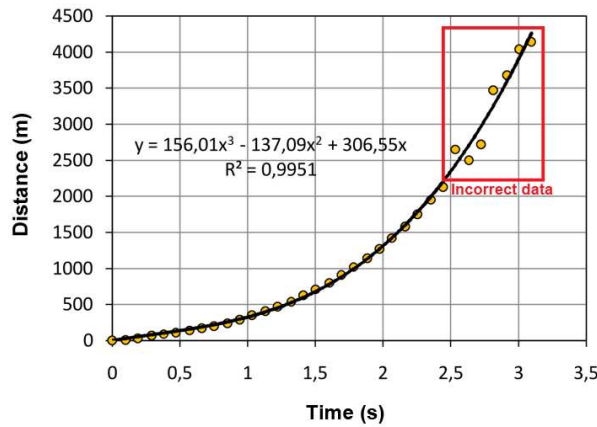
Figure 7. The typical distance-time diagram of the Improved Benkelman Beam Apparatus

In theory, the supporting legs of the manual deflectometer should be far enough from the loaded tires so that they do not participate in the movement of the pavement. Otherwise, the measured values are charged with the so-called foot error (e) *(Figure 8)*. According to the experiences confirmed in Hungary the foot error can be significant as to thin pavements (Kosztka 1978). Because of the outlined problem, the Benkelman-beams with measuring arm of 2:1 have been spread worldwide. In the case of devices like these the distance between the measuring peak (A) and the foot point (B) is twice as long as the distance between the foot point (B) and the meter (C). The extended length is usually enough to place the legs on deformationless area without affecting the controllability of the device (Kosztka 1986). In spite of the developments we have to take foot error into account, as its rate depends on the value of the so-called *co-working length* typical of the pavements (Boromissza 1959). This value may vary within broad limits.
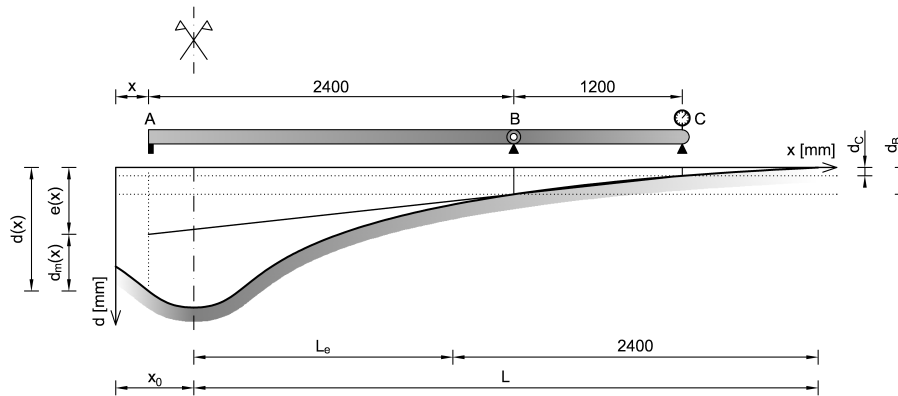

Figure 8. The foot error (e) coming from the support of the measuring arm (B)

The improved manual deflectometer can record the deformation line evolved under load up to 5 meters, so it is possible to estimate the foot error per measured points:

$$c(x) = \left(d_B(x) - d_C(x)\right) \cdot \frac{3600}{1200} + d_C(x) = 3 \cdot d_B(x) - 2 \cdot d_C(x) \tag{1}$$

where:
- $e(x)$ – The value of the foot error evolving from a distance of x from the measuring peak, [mm].
- $d_B(x)$ – Displacement measured at the foot point, [mm].
- $d_C(x)$ – Displacement measured at the meter, [mm].
- 3600 – The total length of the deflectometer, [mm].
- 1200 – Distance between the B and C points of the deflectometer, [mm].

We need to take the foot error into account as to the section of length L_e of the deflection bowl charged with foot error. Taking the foot error into account we can compute the corrected value of the x coordinate point of the deflection line:

$$d(x) = d_m(x) + e(x) \qquad (2)$$

where:

    d(x)   – The value of the deflection, if the axis of the deflection is placed at a distance of x from the measuring peak, [mm].

    d_m(x) – The measured deflection at a distance of x from the measuring peak, [mm].

    e(x)   – The rate of foot error evolving at a distance of x from the measuring peak, [mm].

9   EVALUATING THE MEASUREMENT RESULTS

After the field measurements and pre-processing the data, the first step of the measurement results' evaluation is that we fit a function in numerical way on the measured values, well representing the shape of the bowl:

$$D(x) = \frac{D_0 4r^2}{c \cdot x^2 + 4r^2} = \frac{D_0}{c\left(\dfrac{x}{d}\right)^2 + 1} \qquad (3)$$

where:

    D_0   – The maximum deflection under the loaded disc [mm].

    r   – The radius of the loaded disc [mm], *d=2r*.

    c   – The shape factor typical of the deflection bowl's shape.

    x   – The distance from the centre of the load [mm].

Advantageous feature of the applied function is that it can be continuously differentiated. The first as well as the second derivate can be computed at an optional x place. With the help of the function the complex measurement series (the deflection bowl) can be characterized with two parameters (D_0, c). The detailed description of the suggested function is discussed by Primusz and Tóth (2009).

10 PARAMETERS DESCRIBING THE PAVEMENT'S STIFFNESS

The radius of the circle tangent to the function describing the shape of the deflection bowl at $x = 0$ can be computed in a closed form:

$$R_0 = \frac{2r^2}{c \cdot D_0} \qquad (4)$$

where:

    R_0   – Curve radius, [mm].

    D_0   – The maximum deflection measured at the place of load, [mm].

    r   – The radius of the ideal, round load surface, [mm].
            We set its value typically to 150 mm.

The minimal curve radius is, beside the central deflection, a value that describes the pavement deformation in a simply interpretable way. We can clearly see, if the pavement is deflected by the repeated loads along a small-radius arc, it will get damaged sooner (fatigue).

Knowing the minimum deflection radius and the thickness of the asphalt layers we can compute the strain of the asphalt layer's bottom line:

$$\varepsilon = \frac{h}{2R} \tag{5}$$

where:
- ε – The strain of the asphalt layers' bottom line, [m/m].
- h – The thickness of the bonded layers, [m].
- R – Curve radius, [m].

We usually use µstrain (µm/m) for strain; to do so, we have to multiply the value received in [m/m] dimension by 10^6. The strain is one of the important parameters of the asphalt pavement layers' lifetime, and it is essential for computing the remaining lifetime of the pavement. The distance of the inflexion point of the function that describes the shape of the deflection bowl measured from the place of load (stiffness radius) is:

$$L = \frac{2 \cdot r}{\sqrt{3 \cdot c}} \tag{6}$$

where:
- L – Stiffness radius [mm].
- c – The shape factor typical of the deflection bowl's shape.
- r – The radius of the ideal, round load surface, [mm].

The latest researches at the Forest Opening Up Department (Primusz–Markó, 2010) showed, that the elastic moduli of the pavement's bonded layers (asphalt) and the non-bonded layers below (base layers + subgrade) can be computed if we know the stiffness radius and the thickness of the pavement layers (asphalt) that have cohesion.

11 APPLICATION OF THE METHOD ON A FOREST ROAD AT HÁRMASTARJÁN

The first application of the improved manual deflectometer in practice was realized on the second-class forestry road of Ravazd Forestry of the Kisalföldi Erdőgazdaság Zrt. in Hármastarján. We executed the deflection measurement in both tracks with sampling at every 50 meters. Both the prototype of the measuring device and the measurement process proved that they are appropriate for usage under normal operating conditions. Studying the time needed for the measurement, we can state, that using this procedure, in one hour, we can measure a 1 km section with 50 m sampling.

After the field measurements we processed the deflection measurements with the software described above. At the measurement points we defined the following parameters:
- Central deflection (D_0, mm).
- The shape factor of the deflection bowl (c).
- Minimum curve radius (R, m).
- The elastic moduli of the bonded layers (E_k, Mpa).
- The elastic moduli of the non-bonded layers (E_{nk}, Mpa).

The individually defined values by measurement place were displayed on a condition-evaluation longitudinal profile with the "RR" software developed at the Department. Then we defined the borders of the homogeneous sections that we considered conditionally identical. We computed the standard value of the above-mentioned parameters for the homogeneous sections, and then we continued the further analysis using these values. The standard values of the indicator parameters are summarized in *Table 2*.

Table 2.   Calculated bearing capacity parameters of the studied pavement

Border segment of the homogeneous sections	Central deflection	Curve radius	Asphalt strain	Moduli	
				Bonded pavement layers	Non-bonded pavement + subgrade
[hm]	D_0 [mm]	R [m]	μ [microstrain]	E_k [Mpa]	E_{nk} [Mpa]
0+00					
	1,25	98	306	3620	84
2+25					
	1,85	61	492	2390	64
11+25					
	1,29	99	303	3660	99
21+75					
	1,26	64	469	1990	94
28+25					
	0,89	107	280	3490	106
31+75					
	1,1	72	417	2560	116
39+00					

12 SUMMARY AND CONCLUSIONS

Researchers of the Institute of Geomatics and Civil Engineering at the University of West Hungary developed a new instrument to measure the full deflection basin with Benkelman beam. A new method for the analysis of the deflection basin is also developed.

Both the prototype of the measuring device and the measurement procedure proved that they are appropriate for usage under normal operating conditions. Studying the time needed for the measurement, we can state, that using this procedure, in one hour, we can measure a 1 km section with 50 m sampling. Measurements were made in both wheel path simultaneously. The next parameters were determined after the field measurements:

- Central vertical deflection.
- Shape coefficient of deflection basin.
- Strain of the bottom of the asphalt layer.
- Minimal radius of curvature.
- Young-modulus of the asphalt layer.
- Young-modulus of the granular subgrade.

New results are presented via the case study of a 2nd class opening up forest road.

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