Agronomy Research **14**(3), 790–800, 2016

Soil compaction caused by irrigation machinery

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Abstract. This contribution is focused on the analysis of soil compaction with chassis of a wide-span irrigation machine, Valmont. The sprinkler had 12 two-wheeled chassis (size of tyre 14.9"×24"). During the evaluation of soil compaction, we monitored the values of penetration resistance and soil moisture during the operation of the sprinkler. Considering the performance parameters of the pump, the sprinkler was only half of its length (300 m) in the technological operation. In this area, also field measurements were performed in 19 monitoring points spaced both in tracks and outside the chassis tracks. The analysis showed the impact of compression with sprinkler wheels. The results of average resistance ranged from 1.20 to 3.26 MPa. The values of the maximum resistance ranged from 2.30 to 5.35 MPa. The results indicated a shallow soil compaction; however, it is not devastating.

Key words: penetration resistance, soil moisture, sprinkler, soil.

INTRODUCTION

Soil compaction is a serious problem that adversely affects the productivity of crops, while crop yields are significantly reduced (Lhotský et al., 1991; Défossez & Richard, 2002). It is a process of soil particles relocation, which reduces soil porosity, thereby causing an aeration decrease and an increase in volume density and soil strength (Al-Adawi & Reeder 1996; Hillel, 1998; Brady & Weil, 1999; Hamza & Anderson, 2005). Soil compaction greatly affects the physical condition of the soil profile, especially with the pressure of agricultural machinery in cultivation and harvest (Alaoui et al., 2011; Braunack & Johnston, 2014). The result of this pressure is a technological or secondary compaction of the soil profile (Abedin & Hettiaratchi, 2002), defined with critical values of physical soil properties (Fulajtár, 2005; Carizzoni, 2007), particularly with a high volumetric density and low porosity (Keller et al., 2007).

An overview of the spatial distribution of compacted soil layers can be obtained by measuring the soil penetration resistance, which depends on volumetric density and soil moisture (Lamandé & Schjønning, 2011a). For a precise definition of the extent of compacted soil layers, it is important to determine its vertical and horizontal spatial distribution (Lamandé & Schjønning, 2011b). The critical value of soil compaction for plant growth is dependent on soil type and soil moisture (Schuler & Woods 1992). In terms of soil particle size, compacted sandy soils have little or no ability of spontaneous recovery, while for heavier soils, there are factors that allow reversible processes (regeneration of soil structure) (Mašek, 2005). Soil properties characterize the operating conditions of tractors and influence the load of hydraulic and transmission systems. Therefore, we have to determine the soil properties in operating conditions of a tractor (Majdan et al., 2011). Interaction between the tyre and soil affects the exploitation of machinery in agriculture (Šesták et al., 1998; Rédl, 2009).

Soil compaction increases soil strength and decreases soil physical fertility through decreasing storage and supply of water and nutrients, which leads to additional fertilizer requirement and increasing production cost (Hamza & Anderson, 2005). There are environmental effects of soil compaction (Keller et al., 2013). The effect of compacted soil on the emissions released from soil into the atmosphere were observed for N_2O (Šima et al., 2013) and CO_2 (Šima & Dubeňová, 2013).

The main objective was to investigate the effect of soil compaction with the axles of a wide-span irrigation machine and to evaluate the acquired knowledge and outcomes of the measurement.

MATERIALS AND METHODS

To meet study objectives, field measurements were made in conditions of a farm Kovacs Agro, s.r.o., Hronovce, Slovakia (47°59'46.2"N 18°39'37.9"E). The arrangement of monitoring points was performed according to Fig. 1.

It is a very warm, dry and lowland region with following climatic conditions: Annual mean temperature 9.46 °C; Annual rainfall 620 mm; Number of rainfall days 146; Relative air humidity 77%; Depth of soil freezing from 10 to 23 cm; Annual sun light length 1817 hours; Annual Mean Cloudiness 58%).

The selected field is characterized by Haplic Chernozem and Luvi-Haplic Chernozem on loess, slope 0–1°, a plane without surface water erosion, medium (loamy) soil, according to the granularity code. The total area of the field was 181.31 ha, of which the irrigated area was 180.14 ha, which means a 99.35% coverage.

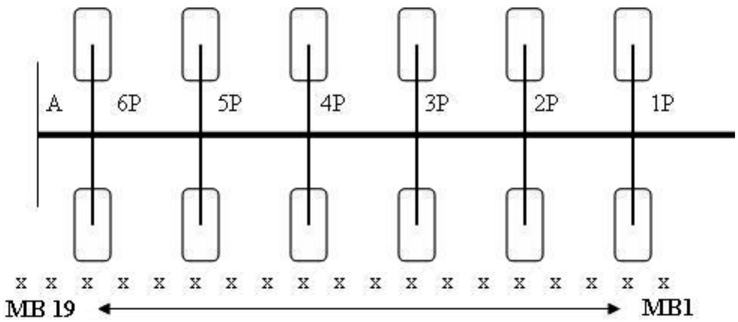

Figure 1. Principe of measurement of soil parameters; A – centre of wide range irrigation machine; P – tower; x – monitoring points; MB – monitoring point.

These points were located not only in tracks of the chassis but also outside them. The number of monitoring points was 19. Field experiments also included the measurement of soil moisture content (WET sensor, equipment, DELTA-T Devices Ltd., Cambridge, UK; HH2 logger, equipment, DELTA-T Devices Ltd., Cambridge, UK) and penetration resistance (Penetrologger Eijkelkamp, equipment, Eijkelkamp, Giesbeek, Netherlands, Fig. 2). The experiments were conducted at certain soil moisture during the operation of the irrigation machine. Penetration resistance was measured simultaneously with the measurement of soil moisture. We used a conical tip with an angle of 30°, which is recommended by the ASAE Standard S313.2 (1994) for heavy and medium soils. The measurement of soil penetration resistance requires a uniform pressing of the cone into the soil (about 3 cm s^{-1}). The penetrologger´s measuring range is 0–10 MPa. This device allows recording the soil profile to a depth of 0.8 m, with a depth resolution of 10 mm. During the penetration, depth is sensed with an internal ultrasound sensor. When measuring the penetration resistance, each measurement consisted of three measurements. The depth of measurements was up to a 40 cm depth. Measured values of penetration resistance were corrected by obtained values of soil moisture (in percentage by weight). This was determined by a gravimetric method. Measuring the moisture with the WET sensor was carried out for each monitoring point three times.

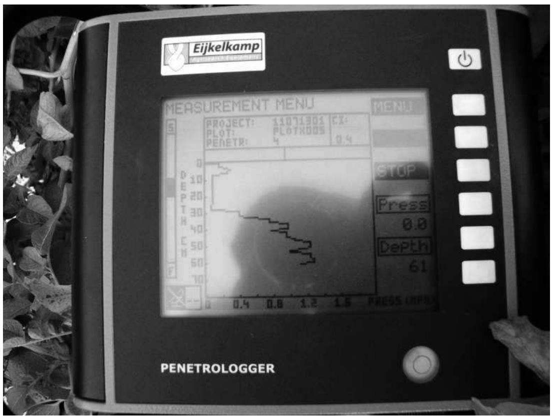

Figure 2. Penetrologger Eijkelkamp – measurement.

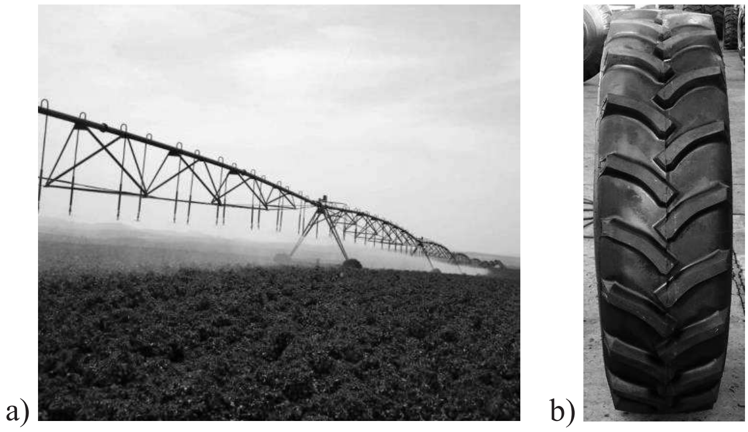

Figure 3. Linear irrigation machines (a) machine and (b) tyre, Valley Valmont, 600 m.

Field measurements were performed for the sprinkler Valley (Valley Irrigation, Nebraska, USA, Fig. 3), linear type, with a length of 594.59 m and the number of chassis

12 (Table 1). Besides the central tower (4 wheels), each chassis was equipped with two wheels. Only a half was always in operation (300 m, the entire irrigation machine moved, but only half sprayed water). A problem was the performance parameters of the pump, which would not cover a reliable technological operation of irrigation equipment for a length of 600 m. A water-pumping station was used as a water source.

Table 1. Technical characteristic of wide range irrigation machine (Valley, Valmont)

Parameter	Value
Sprinkler spacing	192 cm
Number of two-wheeled chassis	12
System length	594.59 m
Type of wheels	high float 14.9" × 24"
Width of wheels	37.8 cm
Power supply	480 V/60 Hz
Maximum speed of system travel	123.6 m h^{-1}
Approx. weight (with water), length of section 49.12 m	2,814 kg
Approx. weight (with water), length of section 54.86 m	3,080 kg
Required run power	20 kW
Type of guidance	below ground – shielded
Length of guidance cable	5,608 m

The effect of the sprinkler chassis on soil compaction was investigated by monitoring the compaction level in wheel tracks and outside them. Measurements were corrected and evaluated according to the Slovak Act No. 220/2004. When the soil moisture was above the correction interval, soil resistance was actually lower, and we had to add 0.25 MPa per each percentage by weight outside the interval. If soil moisture was below the correction interval, it was necessary to deduct 0.25 MPa per each percentage by weight outside the interval. In terms of our research, in clay soils this interval was 18–16% of soil moisture (percentage by weight). Therefore, data were corrected according to Lhotský et al. (1991), and the correction of the results is defined as follows:

$$PO_{KL} = (PO \pm 0.25z), \quad MPa \tag{1}$$

where: PO – measured penetration resistance (MPa); PO_{KL} – corrected penetration resistance according to Lhotský et al. (1991), (MPa); z – difference between the prescribed and measured moisture; its sign depends on whether it is above or below the range.

RESULTS AND DISCUSSION

Variability of soil moisture

Soil moisture is a key feature of the soil for crop irrigation regime. Measurements were conducted at 19 monitoring points in wheel tracks of the sprinkler and outside them. Table 2 shows the descriptive statistics of measurements before the application of irrigation rates. The average value of soil moisture was 10.11% vol. However, the value of the coefficient of variation was high (31.55%). After irrigation, values of soil moisture increased on average by 20.83% vol. The value of the coefficient of variation in measuring the volumetric soil moisture decreased to 17.86%. In this case, there was a positive effect of irrigation and more balanced soil moisture across the whole width of the irrigation machine (Fig. 4).

Table 2. Measured data, soil moisture content, percentage by volume and by weight before and after irrigation

Parameter	Soil moisture content (% wt.)		Soil moisture content (% vol.)	
	before irrigation	after irrigation	before irrigation	after irrigation
Average	8.44	25.78	10.11	30.94
Median	7.76	25.49	9.20	30.90
Modus	8.78	–	10.53	32.80
Standard deviation	2.66	4.74	3.19	5.52
Variance	7.08	22.49	10.20	30.52
Difference max-min	8.47	22.39	10.16	26.30
Minimum	5.39	15.82	6.47	19.30
Maximum	13.86	38.21	16.63	45.60
Sum	160.27	489.83	192.12	587.80
Sample size	19.00	19.00	19.00	19.00
Coefficient of variation	31.54	18.39	31.55	17.86

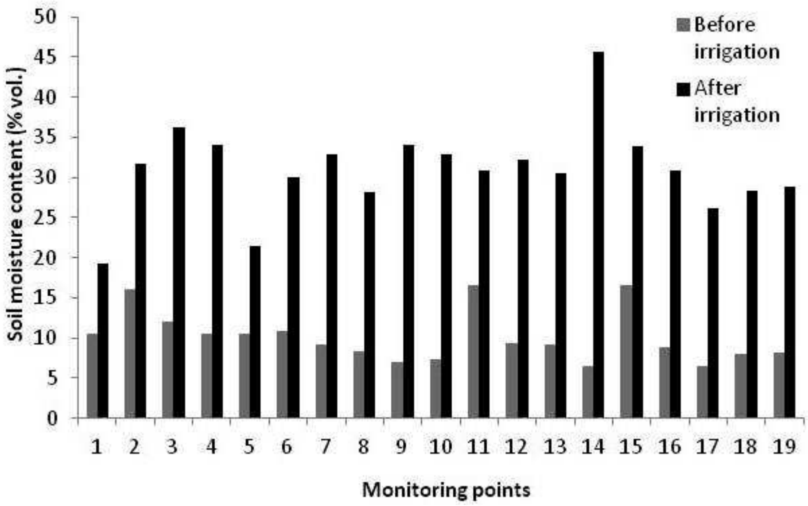

Figure 4. Soil moisture content before irrigation and after irrigation.

Variability of penetration resistance

In determining the variability of penetration resistance, measurements were performed before irrigation. After irrigation, measurements of penetration resistance were sufficiently affected by soil moisture because all values are outside of the range defined by Lhotský et al. (1991). Therefore, a correction factor of humidity was used, and all data were corrected according to the Act No. 220/2004 on the conservation and use of agricultural land. Values of penetration resistance were corrected to 18–16% vol. soil moisture.

It follows from the collected data that the farm extensively applies the principles preventing an undesired impact of agricultural machinery on the soil on the monitored field, since the average value of penetration resistance ranged from 1.20 to 3.26 MPa (Fig. 5). The maximum values of penetration resistance ranged from 2.30 to 5.35 MPa (Fig. 6). The limit value for the maximum soil penetration resistance was exceeded at two monitoring points (P5 and P6).

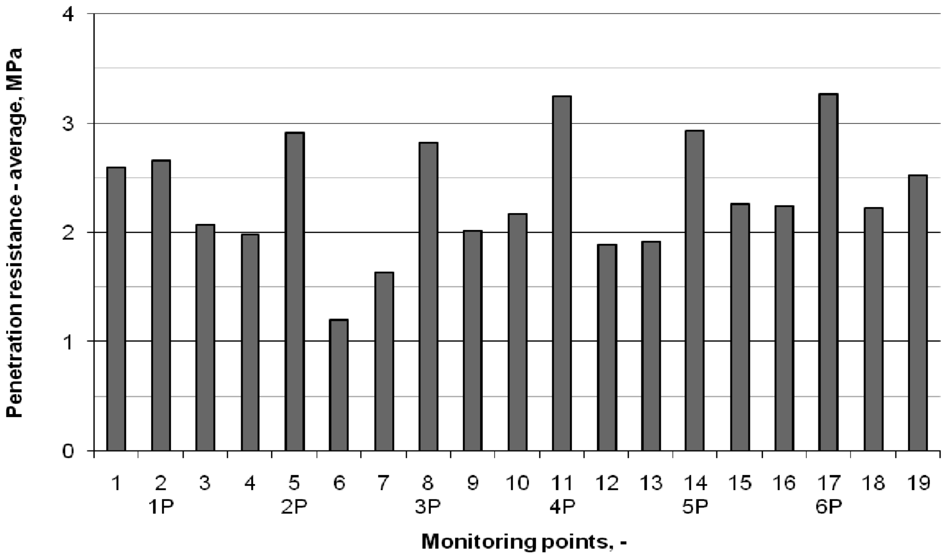

Figure 5. Penetration resistance of soil – average, MPa; P – tower.

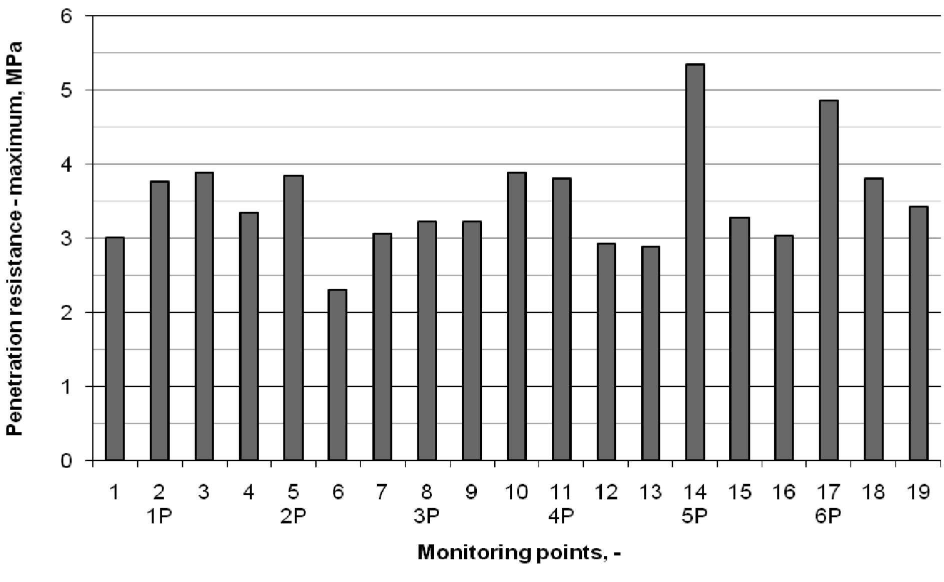

Figure 6. Penetration resistance of soil – maximum, MPa; P – tower.

According to the ASAE Standard EP542 (2004), 2 MPa is the value of penetration resistance which already limits the development of the root system of plants; however, this standard does not distinguish between soil types. The variability of penetration resistance is given by the variability of moisture conditions and passes of machines, too.

When comparing the data obtained, we concluded that penetration resistance increased in wheel tracks of the irrigation machine. The graphical representation shows that penetration resistance in wheel tracks after machine passes is higher than outside of tracks. Fig. 7 shows the secondary compaction which is significant especially in the depth of up to 10 cm.

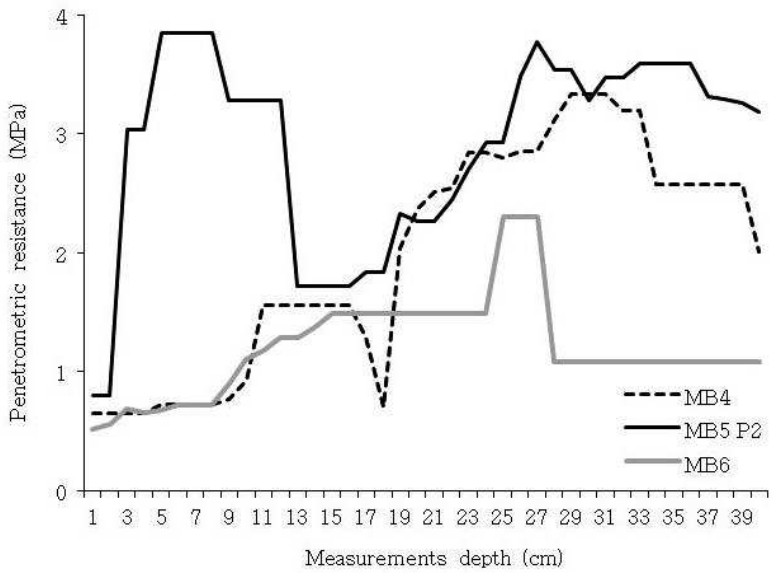

Figure 7. Relationship between penetration resistance and measurement depth in monitoring points: MB4, MB6 – monitoring point outside of chassis; MB5 – monitoring point within the chassis (tower 2P).

Determining the effect of soil moisture on penetration resistance

After application of irrigation depth the value of penetration resistance decreased depending on the depth measurement (Fig. 8). Soil compaction with the impact machine passes is a specific phenomenon that is becoming even more a current topic while it was observed a clear differences in Figs 5–6.

Based on the obtained literatures (Hiller, 1998; Duiker, 2004; Fulajtár, 2005), it can be concluded that it is necessary to evaluate the soil compaction always with respect to current humidity conditions, the presence of a particular crop, soil types, and used machinery. Soil compaction is caused by effects of increasingly heavy machinery on soil as well as tillage and passes under an improper soil moisture. Increasing compaction is affected not only by tractors and harvesters but also by other self-propelled, trailer and semi-trailer machines (Keller et al., 2013). In general, shallow soil compaction is attributed to pressure in the 'tyre-soil' area, while deep soil compaction refers to the effects of the total axle load on soil (Duiker, 2004).

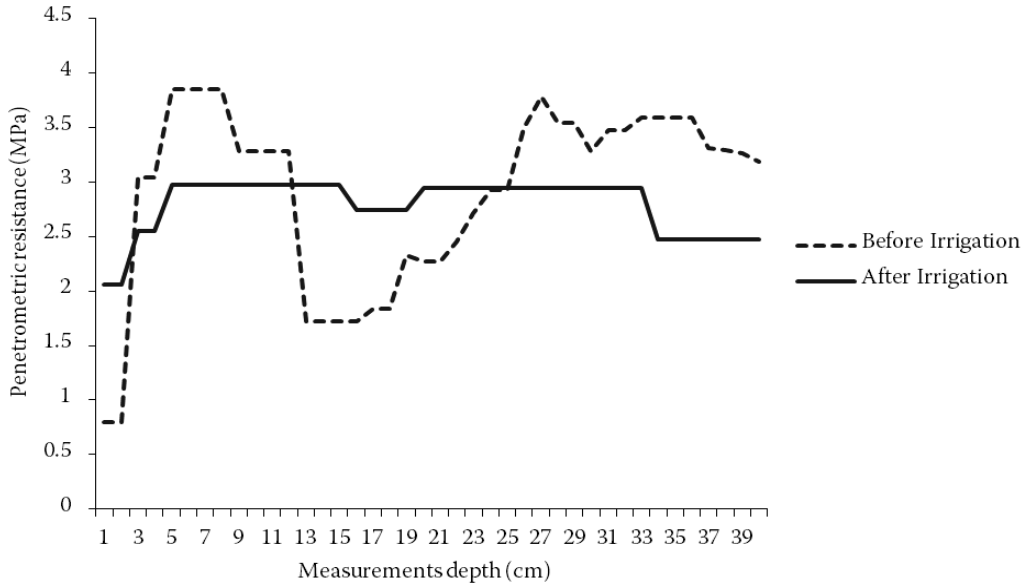

Figure 8. Relationship between penetration resistance and measurement depth in monitoring point MB5, tower 2, before and after irrigation.

When using the wide-span irrigation machine with selected tyres, an effect of the chassis on shallow soil compaction was confirmed. The values of penetration resistance ranged from 0 to 3.13 MPa in tracks and outside them. The highest changes were demonstrated in the tracks of the second chassis (tower). However, it is possible to state that the irrigation machine with its total mass divided into individual chassis does not cause devastating compaction. It is rather only a local and shallow soil compaction which can be removed with appropriate tillage. The soil moisture content is an important factor for passes of machines. The soil moisture content is determined from a disturbed soil sample. Another factor is the total weight of the machine and the total contact area. The number of machine passes on the soil is needed to be monitored and reduced. Joining certain operations can contribute to reducing soil compaction.

Váchal et al. (1983) recommend the reduction of passes after sub-soiling in the first year, to merge machines into aggregates, and to grow deep-rooted crops at least two years after intervention. All the performed measures must lead to creating an optimal soil structure and its protection.

Machine passes on the soil can cause its compression; they can reduce the soil porosity and create barriers to water and air movement in the soil and roots penetration in the soil (Braunack & Johnston, 2014). Soil compaction is determined by several methods. Most of them require soil sampling, time necessary for laboratory analyses, or a long period of field preparation where holes are prepared for ditch sensors.

Probably, the fastest way to determine soil compaction is the measuring of penetration resistance (Carizzoni, M. 2007). The results of penetration resistance on the monitored field confirmed a higher soil resistance in wheels tracks of the irrigation machine. Carrara et al. (2003) state that there are a lot of examples where penetration resistance is used for monitoring the soil compaction.

During the year, the soil responds to machine passes in different ways. Soil resistance to compaction decreases with increasing soil moisture. Humid and light soils have a very low resistance during seedbed preparation and sowing when passes cause compaction of the topsoil and subsoil (Kulkarni et al., 2010), which affects the crop grown during the whole growing season. Other risky periods occur during autumn field operations when loaded machines compact the soil into a high depth (Hůla, 1989). Our values were evaluated in conformance with the values introduced in the Act No. 220/2004. The results have shown a clear effect of irrigation machine wheels on compaction.

The presented act specifies the limit values of corrected penetration resistance ranging from 3.7 to 4.2 MPa at the moisture of 18–16% wt. for clayey soil. Our results have not exceeded these limit values. It means that compaction values harmful for plant growth were not exceeded. However, there was a higher compression in wheels tracks of the irrigation machine.

Solving this issue in relation to soil compaction has focused mainly on a new design of tyres and weight reduction of machines. Before new design of tyres got into production, it was recommended to use double wheels to reduce soil compaction with contact pressures. Controlled underinflated tyres of machines also appear to be suitable for driving on fields. However, new constructions of low-pressure tyres are currently dominating (Javůrek & Vach, 2008¸ Keller et al., 2013). The model of tyres used on the irrigation machine Valmont was also radial on all the axles due to a lower compaction in their tracks.

According to Abedin & Hettiaratchi (2002), the incidence of compacted layers in the soil profile is usually possible to detect only in the spring when the soil profile is evenly moistened. Measurement in summer and in autumn is unreliable because the soil profile can show large moisture differences, which are reflected in the values of soil penetration resistance.

CONCLUSION

There was a positive effect of irrigation and more balanced soil moisture across the whole width of the irrigation machine while soil moisture coefficient of variation changed from 31.55% to 17.86%.

In examining the variability of penetration resistance in dependence on the monitoring point, we found that in wheel tracks of the irrigation machine, penetration resistance is higher than outside of tracks. It ranged from 1.20 to 2.30 MPa and from 3.26 to 5.35 MPa, respectively. Based on the results, we can say that due to a lower weight of the whole machine in comparison with other machines, there was only a shallow soil compaction which not cross 10 cm. However, penetration resistance increased with depth.

The effect of soil moisture on the penetration resistance was observed. Thererofe, irrigation has the effect on penetrometric resistance as well. However, the variability in soil condition across the field affectes the results and the final effect was different for most of the observing points which ranged from 64.1% to 91.6%.

ACKNOWLEDGEMENTS. The paper reflects the results obtained within the research project VEGA 1/0786/14 Effect of the environmental aspects of machinery interaction to eliminate the degradation processes in agro technologies of field crops.

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