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Investigating soil compaction using strain transducer

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Abstract

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Soil compaction has been a challenging problem in agriculture. The parameters affecting soil compaction and their effects should be investigated. Thereby, series of soil sinkage tests were conducted at the University of Mohaghegh Ardabili to evaluate the effect of soil moisture, loading velocity, depth and loading times on soil compaction using strain transducers. Three strain transducers were placed in *x, y* and *z* directions and their displacement was recorded during loading and unloading. Experiments were arranged as a complete randomized factorial design and 3 levels of moisture content and loading velocity and 2 levels of depth and loading time were investigated at three replications. It was found that with moisture increment soil displacement increased whereas increasing loading velocity and depth decreased soil compaction. There was a significant difference between the first and second loading time. The mutual binary effect of moisture content and loading time as well as that of depth and loading times were significant for transducer displacement. Mutual triplet effect of moisture, velocity and depth on the transducer displacement was significant.

Keywords: soil sinkage; displacement; bulk density; moisture; loading time

To make the right decision on the agricultural measures, water, soil and other agricultural inputs require having the right information about the machine and its interactions with the environment. Since soil is the source of nutrition and an environment for plant growth, hence the design of devices that are in contact with soil is important. One of the adverse effects of agricultural machinery traffic on the soil is compaction. A part of that occurs because of tillage operation especially when mouldboard plough is used. Another part can be due to traffic of the tractors and agricultural machinery traffic during tillage, planting, harvesting and other agricultural operations. Knowing and understanding the relationships between the soil properties and machine system would be helpful to determine the effect of compaction on soil properties. Evaluation of compaction effects on soils due to its negative effect on crop growth and production is necessary. Soil compaction can easily reduce production efficiency up to 10% and degrade soil structure and reduce water flow through the soil, which leads to reduced soil quality (Duiker 2002). Soil compaction under tractor wheels has increased because of mechanized farming in recent years. By accepting compaction effect on soil degradation and erosion, ways to manage and decrease it must be find. Precision farming can reduce it; however, modern tractors are heavier than those in the past and with the high power and capacity to draw large implements increased the risk of soil compaction.

Stress applied to the soil surface associated with soil strain results in a rearrangement of the solid particles if the internal soil strength is exceeded. Hence, a coupled soil stress and strain measurements are required so that compaction be understood completely (Horn et al. 1995). To clarify the effect of the dynamic load, tyre inflation pressure and wheeling frequency, series of experiments were conducted by (Wieremann et al. 1999). A stress state transducer was used to measure stress beneath the tyre attached to a displacement transducer system. Stress transducer was installed at a depth of 10 cm beneath soil surface. It was connected to displacement transducer by a rigid tube. Thus, the vertical and horizontal displacement of stress

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transducer was measured as wheeling progressed. Total vertical strain was calculated from data of strain transducer plus the measured rut depth. Three dynamic loads of 13.2, 19.8 and 25.3 kN at three inflation pressures of 41. 83 and 124 kPa for two passes of tyre were investigated. The results show that increasing dynamic load and the inflation pressure had a highly significant impact on soil stress. The results for the second pass in comparison to the first pass showed a significant increment.

Way et al. (2005) used three strain transducers to determine soil strain in loose sandy loam soil in a soil bin beneath of an 18.4R38 radial-ply tractor drive tyre (soil strain is defined as the change in transducer length divided by the initial length of the transducer which was installed in the soil). Its forward velocity was 0.15 m/s with 15% of slippage. Transducers were inserted in the soil with their initial lengths in the longitudinal, lateral and vertical directions so that the orientation of the transducers was mutually orthogonal. The initial depth of the midpoint of the transducers was 220 mm beneath the undisturbed soil surface and it was directly under the centerline of the tyre path. The dynamic load on the tyre was 25 kN and its inflation pressure was 110 kPa. As the tyre approached, in the longitudinal direction the soil first compressed, then elongated, and then compressed again. In vertical direction, it was compressed and elongated in lateral direction. The mean final lateral strain was 0.127 (positive value shows elongation) which was 64% of the mean final vertical strain, –0.2. The mean final longitudinal strain was –0.027, which was 13% of vertical strain. The mean final volumetric strain from strain transducers was –0.099, which was 35% of the mean change in the volumetric strain calculated from soil core samples, –0.286. They concluded this difference was because of the greater dimension of the lateral transducer with initial endplate spacing of 117.5 mm while lateral dimension of the cores was 69 mm.

In a field test by (Kinney et al. 1992) soil compaction was evaluated by measuring soil strain under the tractors equipped with single rear wheels, dual rear wheels and steel track. All tractors were of nearly equal mass. Four strain transducers were installed at 200 mm intervals along the centreline of the tyre path at the depths of 100, 150, 200 and 300 mm beneath the soil surface. It was found that in the 100–240 mm soil layer the tractor with single rear tyre caused 55% more final soil strain than that with the inside wheel of dual-rear wheel and 70% more than the track. The outside wheel of the dual-wheel tractor produced the least value of soil strain. It was likely due to the lower inflation pressure of outside tyre – hence, inside wheel has to carry the majority of the tractor weight. Çarman (1994) conducted field tests to measure soil compaction under the rear tyre of a two-wheel drive tractor. The dynamic load on the rear tyre varied from 7.27 to 13.5 kN and the forward velocity varied from 0.78 to 2.5 m/s. The cone index, bulk density, shear strength and tyre shrinkage were measured. It was found that increasing the tyre load at the given range of forward velocity increased cone index, bulk density, shear strength and shrinkage. Tyre load change was more effective on soil compaction than the forward velocity.

The objectives of these test was to quantify the possibility of usage of strain transducers as a tool for evaluating soil compaction and also for evaluating the effect of moisture content, loading velocity, depth increment and loading time on soil compaction.

MATERIAL AND METHODS

Series of experiments to determine the strain transducer behavior against compression were conducted at the University of Mohagheg Ardabili workshop using the soil box. An experimental device was developed; it is able to conduct three soil mechanical tests of sinkage, penetration and direct shear, by which soil cohesion, internal friction, stiffness, soil constant and strength can be determined. In this research, only sinkage scheme was used for testing. The system included mechanical parts as follows (Fig. 1): chassis, main rails, rails for electric motors, mechanical jacks, screw transmissions, soil box, and pressure-plate. For sinkage test, electromotor power was used to vertical movement of rectangle plate to press soil downward. The length, width and height of soil box were 70 × 60 × 80 cm, respectively. A pressure plate with dimensions of 30 × 30 cm and thickness of 6 mm was used for soil sinkage.

Electromotor power was transferred via drive shaft to a jack that was able to lift 1,000 kg (Fig. 1). The jack was connected to the sinkage plate by a bar that goes through the fixed plate and an S type load cell with the maximum capacity of 1,000 kg

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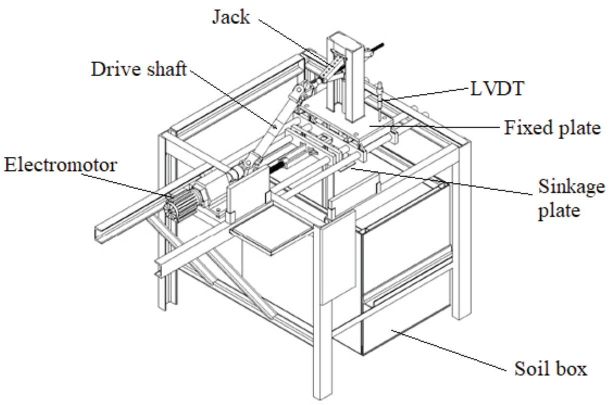

Fig 1. Scheme of developed system was used for sinkage test

was installed on this bar to measure force required for plate sinkage. To control movement velocity of the sinkage plate an inventor (RS-485) was used to change the frequency of electric current and then different revolution speeds of the electromotor were created.

The experiments were conducted in a loam soil (sand 45.66%, silt 29.336% and clay 25.008%) and bulk density of 1,200 kg/m^3. Soil box was filled up to the height of 60 cm, hence its volume was 0.336 m^3 and soil mass required for creating the mentioned bulk density was 302.4 kg, which was determined by $\rho = m/v$ formula. For creating homogenous bulk density, the height of soil box divided to 12 sections of 5 cm and also required soil mass was divided by 12 and each portion of soil (25.2 kg) filled in the determined volume.

Vertical movement of the sinkage plate was measured using the strain transducer (Model DLH-A-50; Copeland, USA) with sensitivity of 3.64 mv·v^{-1} and max. displacement of 50 mm. Three strain transducers were located in the soil with their initial length in the x, y and z directions. Strain transducer was equipped with a circular palate at each end (Fig. 2). The initial depth of the midpoint of the transducer was 200 and 300 mm beneath the soil surface and they were directly under the pressure plate. Jack inserted the maximum pressure of 98 kPa on the pressure plate. The strain of the strain transducers located in x and z directions was very low and was neglected in the soil compaction analysis. All data from the load cell and strain transducers were logged to laptop via data logger (Model: DT800; dataTaker, Scoresby, Australia).

After placement of the transducer, the data recorded by data logger were considered as the actual initial endplate distance; after compression, the endplate distance was considered as final endplate space. Since soil only displaced in vertical direction, soil initial volume (V) was determined from Eq. (1):

$$V = A \times l_i \qquad (1)$$

where: l_i – initial endplate distance (m); A – pressure plate area (m^2)

Soil volume after compression was computed from Eq. (2):

$$V = A \times l \qquad (2)$$

where: l – endplate distance of transducer after compression (m)

Final bulk density was calculated by Eq. (3):

$$\rho/\rho_i = V_i/V \qquad (3)$$

where: V_i – initial volume (m^3); V – final volume (m^3); ρ_i – initial bulk density, 1200 kg/m^3; ρ – final bulk density (kg/m^3)

RESULTS AND DISCUSSION

Fig. 3 shows the maximum transducer displacement at the depth of 20 cm, loading velocity of 2.2 mm/s at the first loading as soil moisture content increased from 10 to 20%. Max. compression of 18.88, 22.6 and 28.03 mm was occurred at moisture levels of 10, 15 and 20%, respectively. After removing load transducer elongated for about 5.5 mm and final displacements of 13, 15.82 and 22 mm were obtained. This figure also shows that for all

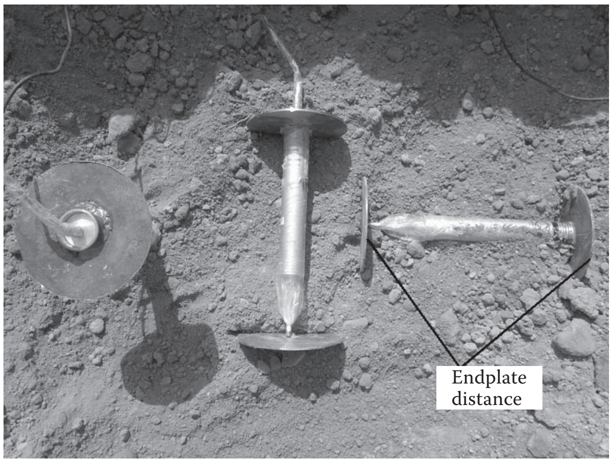

Fig. 2. Situation of transducers inside soil profile left to right, vertical, lateral and longitudinal

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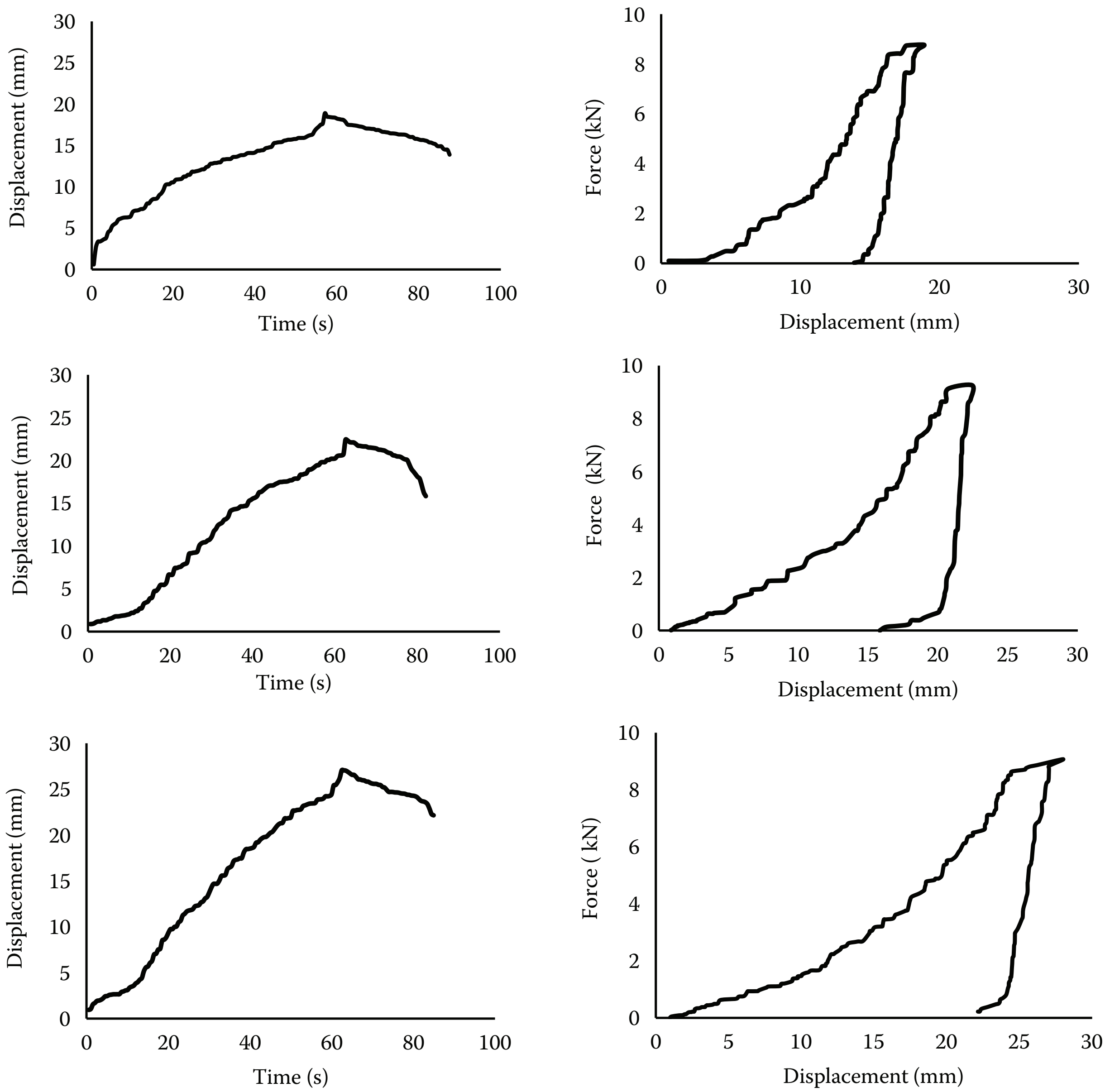

Fig 3. Strain transducer compression and elongation (left), displacement during loading and unloading (right)

the treatments and replications the maximum loading of 9 kN was applied, hence displacement was increasing because of soil moisture content increment. In terms of compression and elongation values of displacement, it can be concluded that moisture content was effective on the compression of soil and was not significant to the elasticity of the soil.

Analysis of variance showed that all main factors of moisture, loading velocity, depth and loading times were highly significant on the transducer displacement. The mutual binary effects of moisture on the loading time were significant at the possibility level of 5% and the effect of depth on the number of loading was significant at the possibility level of 1%. The triplet mutual effect of moisture on the loading velocity and depth was significant in the possibility level of 1%.

Fig. 4a shows the Duncan's multiple range test results for the effect of moisture content on the displacement of transducer. There was a significant difference between treatments. Moisture content increasing from 10 to 20% increased displacements from 10.2 mm to 14.85 mm. Soil critical moisture content was 22%, which determined conducting the standard Proctor test. Strain displacement revealed

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Table 1. Analysis of variance for the effect of moisture (M), velocity (V), depth (D) and number of loading on soil displacement (T)

Source	Degrees of freedom	Sum of squares	Mean of squares	*F*-value	*P*-value
M	2	389.94	194.96	102.62**	0.000
V	2	423.03	211.51	111.33**	0.000
D	1	124.98	124.98	65.78**	0.000
T	1	6,939.07	6,939.07	3,652.32**	0.000
M × V	4	5.89	1.47	0.77ns	
M × D	2	10.67	5.33	2.81ns	0.0670
M × T	2	15.28	7.642	4.02*	0.0221
V × D	2	11.81	5.90	3.1 1ns	0.0508
V × T	2	5.32	2.65	1.40ns	0.2553
D × T	1	25.72	25.72	13.53**	0.0004
M × V × D	4	12.20	3.05	1.61ns	0.1823
M × V × T	4	28.85	7.21	3.79**	0.0074
M × D × T	2	0.98	0.492	0.258ns	
V × D × T	2	5.37	2.86	1.51ns	0.2279
M × V × D × T	4	10.89	2.72	1.43ns	0.2318
Error	72	136.79	136.79	1.90	
Total	107	8147.16			

**highly significant; *significant; ns – not significant

that by increasing soil moisture under critical values, soil compaction increased. (Mosaddeghi et al. 2000) reported similar results about the effect of moisture content on bulk density variation. They found that the max, bulk density of 1.53 Mg·m^{-3}, which was above the critical value (1.43 Mg·m^{-3}), occurred at the plastic limit. Söane and Owerkerk (1994) also indicated that soil moisture content is an important factor affecting soil compaction.

It was found that the effect of loading velocity on the soil compression was significant and increasing velocity reduced the soil compression (Fig. 4b). The maximum transducer displacement of 14.95 mm occurred at the loading speed of 1.6 mm·s^{-1} and it declined to 10 mm at the loading speed of 2.8 mm·s^{-1}. Szymaniak and Pytak (1999) investigated the effect of forward velocity of 5, 10 and 15 km·h^{-1} using different tyres and different inflation tyre pressures on longitudinal and vertical soil deformation. They found that an increase of riding velocity always decreased soil vertical deformation. Vertical soil deformation at forward velocity of 5 km·h^{-1} was at least three times greater than at the velocity of 15 km·h^{-1}. The effect of velocity was more pronounced for high inflation pressures.

Table 2 shows that the depth increment and loading times were significant on transducer displacement. It should be mentioned that compression at the first time loading was 4.5 times more than at the second time loading. Mosaddeghi et al. (2000) showed that the tractor pass was important on the soil bulk density and bulk density at the second pass was higher than the first time, however bulk density change was higher at the first pass.

Fig. 5a shows the mutual binary effect of the moisture content and loading times on soil compression. For both loading times the strain transduced displacement increased with increasing soil moisture

Table 2. The effect of depth and loading time on transducer displacement

Depth (cm)	Transducer displacement (mm)	Loading times	Transducer displacement (mm)
20	13.55[a]	1	20.5[a]
30	11.4[b]	2	4.5[b]

different letters show there was significant difference between treatments

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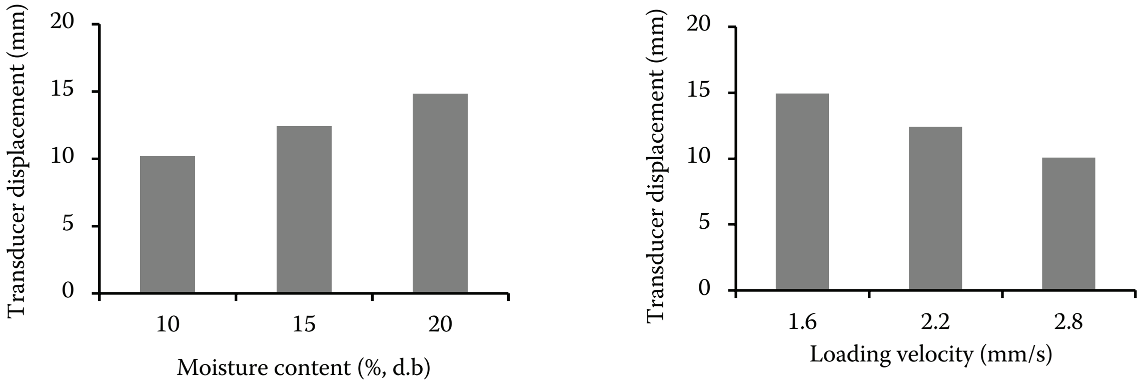

Fig 4. Soil moisture content effect (a) and loading velocity effect (b) on the transducer displacement

content and the max. displacement of 23.32 mm was obtained at moisture content of 20% in the first loading and the min. value of 2.63 mm was at moisture of 10% at the second time loading. On average, at all moisture levels displacement at the first loading was 5 times higher than at the second loading. Mosaddeghi et al. (2000) found that the effect of interaction of moisture and number of passes on soil compaction was significant.

The mutual binary effect of depth and loading times on soil compression (Fig. 5b) clarified that the effect of loading time was much more significant than depth increment effect. Hence, the maximum compaction happened in the first time loading.

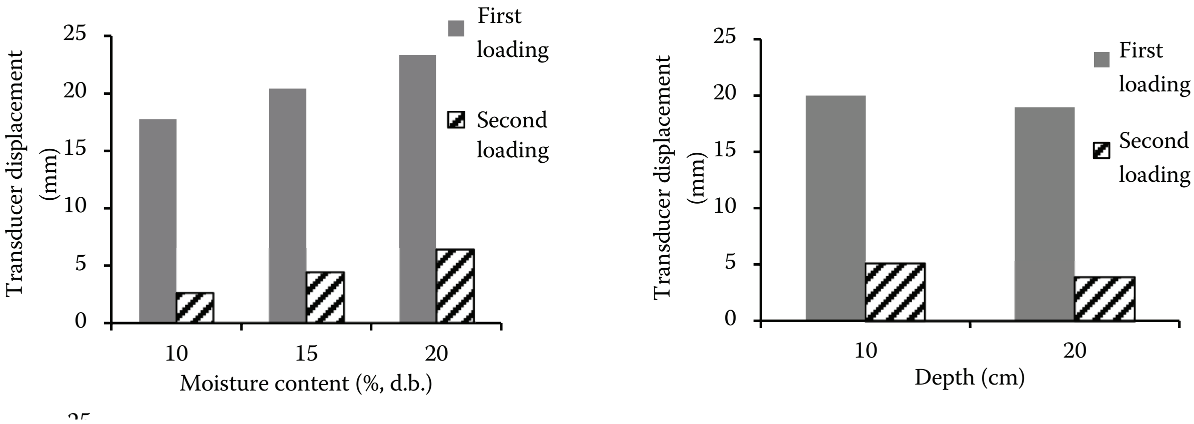

Fig 5. The mutual binary effect of moisture (a), depth (b), and loading time on transducer displacement

Table 3. Mutual triplet effect of moisture, velocity and depth on the transducer displacement

Moisture (%, d.b.)	Loading velocity (mm/s)	Loading times	
		1	2
10	1.6	21.56^{bc}	4.38 ^{hi}
	2.2	17.825^{e}	2.536^{ijk}
	2.8	13.48^{f}	0.99^{k}
15	1.6	22.31^{bc}	7.393^{g}
	2.2	20.47^{cd}	3.86^{ij}
	2.8	18.5d^{e}	1.9^{jk}
20	1.6	25.46^{a}	8.46^{g}
	2.2	23.48^{ab}	6.41^{gh}
	2.8	21^{c}	4.24^{hi}

different letters show there was significant difference between treatments

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Mutual triplet effect of moisture, loading velocity and loading time showed the maximum displacement of 25.46 mm that occurred at the highest moisture content of 20% and the lowest loading velocity of 1.6 mm/s at the first loading. Also the max. displacement for the second loading was observed at the same moisture and loading velocity. Yet, the minimum displacement of 0.99 mm occurred at the lowest moisture content and the highest loading velocity of 10% and 2.8 mm/s, respectively. Also minimum displacement of 13.48 mm occurred at this setting for the first loading.

CONCLUSION

It was found that the strain transducer is a proper device to measure and evaluate soil compaction and to investigate the parameters affecting it. Also by using strain transducer, the soil behaviour was determined during compaction.

Soil vertical displacement increased as soil moisture increased and with increasing loading velocity soil displacement decreased. Soil was loose in the beginning of tests; hence soil displacement in the first loading was much higher than in the second loading. Soil displacement at the depth of 10 cm was more than 20 cm.

In terms of compression and elongation values of displacement, it can be concluded that moisture content was effective for the compression of soil and was not significant for the elasticity of the soil.

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