Matric suction effect on distribution of stresses caused by vehicle wheels on a bare silty sand

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Abstract. - Soil compaction in cropping systems, caused by the external pressure of machinery, creates impermeable layers that restrict water and nutrient cycles reducing agricultural production. To evaluate the matric suction effects on distribution with depth of stresses in a soil, caused by the use of agricultural machinery, Jet Fill tensiometers were installed at two different depths (i.e. 0.15 m, 0.30 m) in a soil profile constituted by silty sand with gravel (SM); to register the increments on subsoil vertical stresses, two miniaturized load cells (i.e. 16. 5 mm in diameter) were installed in a horizontal position under the centre line of the vehicle wheels' path, at approximately 0.15 m and 0.30 m depth. Care was taken to calibrate the load cells in field conditions. A vehicle was made to pass over the soil surface, at a speed less than 5 km/h; the tyre inflation pressure applied on wheel was 380 kPa. Response of load cells to vehicle loading was evaluated at different average matric suction measured on soil profile. Finally, measured stresses have been compared with values obtained by applying well-known elastic theoretical methods used to assess stresses applied by tyres on bare soils. The corresponding results show that the increment of vertical stresses decreases as matric suction increases, and a good correlation between measurements and simulations of the increment on subsoil vertical stress.

Key words: Soil compaction, Matric suction, Vertical stress, Wheel compression, Load cells.

1 Introduction

It takes a second to compact the soil, but it takes a generation to recover it; therefore, soil compaction caused by machinery has increasingly recognized as a considerable problem on agricultural soils.

The measurement and simulation of stress in soil is a challenging task. Many researchers (Keller 2005 [1]; Arvidsson et. al. 2007 [2]) have investigated the effect of loading characteristics (tyre parameters, wheel load) in order to predict the increment on subsoil vertical stress; they used the equations formulated by Boussinesq (1885) [3] and later modified by Fröhlich (1934) [4] in which the increment of subsoil vertical stress under a point load is calculated; Also, by dividing the contact area into subareas representing point loads, increment on subsoil vertical stresses beneath a tyre can be simulated with Söhne model (1958) [5]. On the other hand, some authors

have studied the soil matric suction of samples under different levels of compression stress in conditions relevant for compaction agricultural soil (Larson & Gupta 1980 [6], Wulfsohn et. al. 1998 [7], Tarantino & Tombolato 2005 [8], da Veiga et.al. 2007 [9]). In their results soil suction remained quasi-constant or increased for compressive stress smaller than a given stress threshold. In contrast, Tarantino & Tombolato (2005) [8] studied the change of suction after compaction on clay and reported that suction decreased systematically.

Most of the models and papers have neglected an important stress variable for unsaturated soils: That is the matric suction. Matric suction is fundamental when solving engineering problems associated with unsaturated soil mechanics. In agricultural soils, it affects seriously in soil compaction.
The present work deals with the variation of soil matric suction under the application of increment of vertical

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stress caused by the passage of a vehicle in soil. The objectives of this study are:

Table 1. Tyre dimensions, tyre inflation pressure p_{tyre}, recommended tyre inflation pressure $p_{recommended}$ and wheel load F_{wheel} of the equipment used in the field experiments.

No.	Vehicle	Tyre size	Tyre inflation pressure, (kPa).		Wheel load, kN	Comments
			Actual p_{tyre}	Recommended $p_{recommended}$		
2	Mini Truck MITSUBISHI CANTER FE15OE03	LT 205/85 R16	380	350-420	16	Rear wheel (with maximum operating capacity)

(a) To analyze the measurements of vertical stress distribution, with load cells, below tyres for a predetermined vehicle of tyre characteristics and wheel load.

(b) to determine relationships between characteristics of measured stress distribution (e.g. maximum measured stress, shape of stress distribution).

(c) to measure the matric suction in the soil, at 0.15 m, 0.30 m and to evaluate their variation due to passing of a vehicle.

(d) to propose a well-known elastic theoretical method like Boussinesq (1885) [3] and Söhne (1958) [5] to compare their results with the load cells measurements and to predict the distribution of contact stress beneath tyres at predetermined depths.

2 Materials and methods

2.1. Experimental site and vehicle properties

For the present study, a soil profile constituted by silty sand with gravel (SM, 45.2 % sand, 25.4 % silt, 19.4 % gravel, 10.0 % clay) from a particular place located in Sucre-Bolivia was used (Fig. 1). The soil on the experimental field has a liquid limit equal to 22.30 % (LL), a plastic limit equal to 14.50 % (LP), a plasticity index equal to 7.8 % (IP) and a specific gravity of 2.65 (Gs).
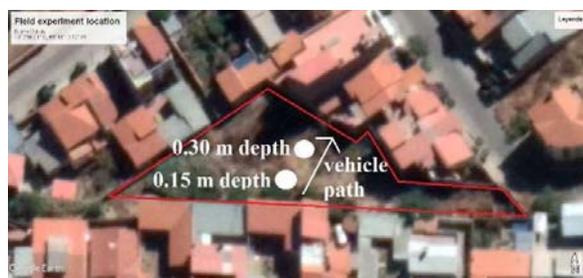

Fig. 1. Location of the experimental plot in the field (red line). The white solid circles indicate the position of tensiometers at 0.15 m and 0.30 m depth, and the white arrow indicates the path of the mini truck on the wheeling event.

From December, 2019 to January, 2020 two field experiments were carried out with a mini truck with $2M^3$

of full capacity in Sucre, Bolivia. The vehicle was used to pass over the soil at 5km/h speed in every field experiment. The December 2019 field experiment was carried out after raining (at a gravimetric water content of 18.89 % at 0.15 m depth and 14.62 % at 0.30 m depth); the January 2020 field experiment was performed on a sunny day (at a gravimetric water content of 8.11 % at 0.15 m depth and 11.73 % at 0.30 m depth). Tyre parameter and wheel load of the vehicle used in both field experiments are summarized in (Table 1). The tyre inflation pressure was chosen according to recommendations of tyre manufacturer manual.

2.2 Measurement of vertical stress distribution and contact area below tyres.

Distribution of the increment of subsoil vertical stress below tyres was measured by compression load cells that were installed in the subsoil at 0.15 m and 0.30 m depth. Each compression load cell (Model DS EUROPE (Milan, Italy) SERIES BC 302) has a 16.5mm diameter, height of 5.5mm (Fig. 2). The sensors (two) were placed under the tyre center axis of the footprint of the wheel, which was assumed rectangular shape. The contact area between tyre and soil surface was measured in situ with paper sheets. The shape of the load cells is:
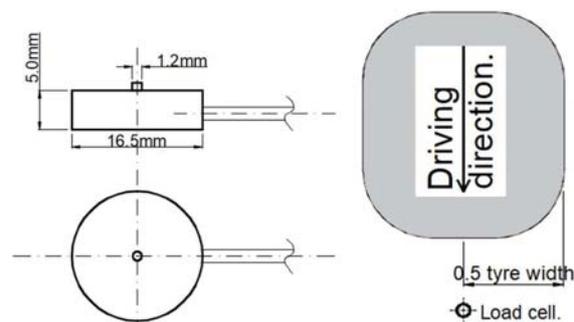
Fig. 2. BC 302 load cell shape and position on the field around the test conducted.

2.3 Test procedure

From November, 2019 to March, 2020, Jet Fill tensiometers were installed in the soil field experiment location in the position of (Fig 1) in order to measure the matric suction at two depths (0.15 m and 0.30 m). A

tensiometer (standard or Jet Fill) measures the force with which water is held in the soil by the soil particles. This force, referred to as matric soil suction, tension, or potential indicates how tightly the water is bound in the soil (2725ARL Jet Fill Tensiometer) [10]. The basic components of tensiometer include a porous ceramic cup, a plastic body tube, a Jet Fill reservoir and a vacuum gauge. The ceramic cup is placed in good hydraulic contact with the soil and allows transfer of water into and out of the tensiometer body according to the tension in the soil. The Vacuum inside the tensiometer body equilibrates with the soil water tension, and the dial gauge provides a direct readout of the tension. The practical limit of a tensiometer is 80-85 kPa due to the effect of cavitation.

The increment of vertical stresses in the soil profile was measured with compression load cells (DS Europe Series BC 302) at two depths (0.15 m and 0.30 m) during the two wheeling events (Fig. 3). Compression load cells (also called sensors or stress transducers) are devices that consists of a metal element that is introduced to a change through tension (pulling apart) or compression (pushing together) forces, and interior strain gages that sense this change, which is sometimes referred to as deflection. Strain gages consist of a thin, continuous, compact, metallic foil pattern, insulated and mounted to the interior of the load cell with proprietary adhesives. This foil wire has a specific resistance that is directly proportional to its length and width. As the load cell bends or stretches, the strain gages move with it. For the compression load cells used in the present study (BC 302), compression shortens the gage, decreasing its resistance. Their range of measurements are from 0 to 700 kPa.

Fig. 3. Left: the vehicle tyres pass the more closely to the Jet Fill tensiometers installed. Right: BC 302 load cells were inserted horizontally near Jet Fill tensiometers; the pit wall is far enough away from the zone of influence of the tyre.

On the two wheeling experiments, compression load cells were installed at two depths (0.15 m and 0.30 m) in the soil by two ways:

- In the field test after raining, on December 2nd 2019, the sensors were installed by excavating 0.15 m and 0.30 m of the soil. After the sensors were installed, the soil was backfilled. Therefore, the original structure of the top soil was destroyed. (Keller 2005 [1]; Arvidsson et. al. 2007 [2])

-In the field test on a sunny day, on January 29th 2020, the sensors were installed by lateral insertion from a pit in a previous hole punched laterally on the wall. Therefore,

the original structure of the top soil above compression load cells remains undisturbed. (M. Lamandé & P. Schjønning) [11].

It was decided to use two different methods for installing the load cells because Keller et. al. (2014 [12] and 2016 [13]) revealed that soil properties had little influence on the measurements of increase of the vertical stress and the distribution with depth of it, could be well described by the classical Boussinesq solution. Therefore, it seemed reasonable to assume, for this study, to do not expect differences between the measurements in the two different ways of inserting the compression load cells (by digging the soil and by lateral insertion).

For the method of lateral insertion of compression load cells, it was required a pit excavation of approximately 5 m long, 1 m wide and 1 m deep. Once dug the pit, horizontal holes (with approximately the same dimensions of the load cells) were drilled on the lateral wall of the pit with a specially constructed mechanical piece. The holes were approximately 1 m apart in the driving direction in order to secure that the stress readings at the lower depth (0.30 m) were not influenced by soil disturbance above the transducer. The compression load cells were placed in the drilled horizontal holes. One load cell was installed for each of the two depths, which was located just for the pass of the tyre foot print center above it.

The distance between the pit wall and the load cells heads was 0.60 m (Fig. 3, 4 5) to be out of the bulb of pressure of the tyre and ensure that the presence of the pit did not influence the increase in stress.
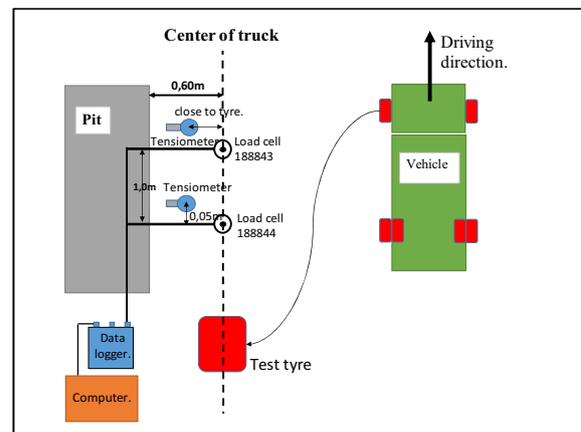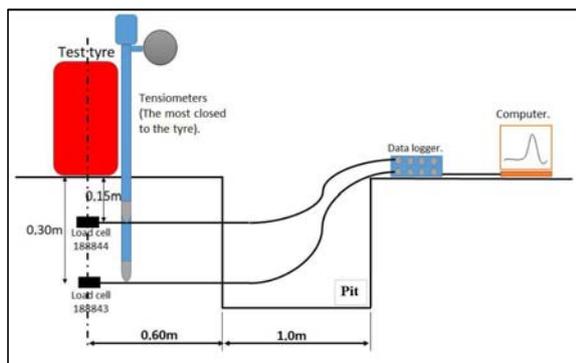

Fig. 4. Schematic top view of the experimental setup and the measurement procedure (not drawn to scale). The distance between the pit wall and the load cells heads was 0.60 m. The two tests of vertical stress increase in the tyre-soil interface actually took place in the field selected (M. Lamandé & P. Schjønning) [11].

For the particular case of excavating 0.15 m and 0.30 m of the soil, there was no need to dig a pit and just care must be taken in order to ensure that compression load cells were placed below the tyres center in the wheeling event.

Before the field tests on the wheeling events, the load cells were calibrated according to the field conditions with the purpose to guarantee a good contact between the load cells and the surrounding soil. An idea of the accuracy of the stress measurements can be gained when the stress is measured in a plane parallel to the soil surface (Keller 2004 [14]). Trautner (2003) [15] observed that the measured stress was much higher when the load cells were placed on a wooden board compared with when the load cells were placed directly in the soil.

Along the two wheeling events carried out, too much care was taken in to account in order to keep the vehicle tyres to the installed Jet Fill tensiometers very close to each other, with the purpose of capturing the soil matric suction modification zone with the porous ceramic cups of the tensiometers. (Fig.4) and (Fig.5) show two schematics views of the experimental setup and the measurements procedure conducted along the two wheeling events in the field experimentation site.

Cylindrical soil cores (50mm inner ø, 50mm height) were sampled along the wheeling events realized at two specified depths in the field. The samples were taken to laboratory, weighed and then dried in an oven at 105°C for at least 24 hours. Afterwards, they were weighed again to determine the gravimetric water content, void ratio, porosity and saturation degree.

Fig. 5. A schematic cross section of the experimental setup across the driving direction. Two load cells were inserted at two depths below the soil surface (0.15 m and 0.30 m) and located at the center of the test tyre passing. In order not to affect the bulb of pressure of the tyre-soil interface, the distance between the pit wall and the load cells heads was 0.60 m (M. Lamandé & P. Schjønning) [11].

2.4 Matric suction measurements

From November, 2019 to March, 2020, Jet Fill tensiometers were used to measure soil matric suction in situ in the soil field experimentation site at two depths (0.15 m and 0.30 m) three times a day: In the morning (8:00 a.m.), in the afternoon (14:00 p.m.) and in the evening (18:00 p.m.). The purpose was to record the value of matric suction when the wheeling events occurred and then, see if there is an effect of the matric suction with the increase of vertical stress in the soil profile at the same

two depths (0.15 m and 0.30 m) by wheeling over the load cells due to the rear left wheel of the vehicle.

2.5 Calculation of the increase of vertical stress in soil

On the two wheeling events, calculation of the increase of vertical stresses in soil was made based on the equations of Boussinesq (1885) [3] and Söhne (1953) [5]. Both under the left rear wheel of the mini truck, with a contact area of 386 cm^2 (on the wheeling event after raining) and 365 cm^2 (on the wheeling event on a sunny day); The tyre tested, wheel load and tyre inflation pressure was registered in (table 1).

Eqn (1) to Eqn (3) correspond to the Boussinesq Solution for calculation of vertical stresses from a rectangular load.

$$\Delta\sigma_z = q \cdot I_z \qquad\qquad Eqn\ (1)$$

$$I_z = f(m', n') \qquad\qquad Eqn\ (2)$$

$$
\begin{aligned}
I_z &= \frac{1}{4\pi}\left[\frac{2m'n'\sqrt{m'^2+n'^2+1}}{m'^2+n'^2+m'^2n'^2+1}\left(\frac{m'^2+n'^2+2}{m'^2+n'^2+1}\right)\right.\\
&\left.+ tan^{-1}\left(\frac{2m'n'\sqrt{m'^2+n'^2+1}}{m'^2+n'^2-m'^2n'^2+1}\right)\right]
\end{aligned} \qquad Eqn\ (3)
$$

The Söhne model is based on the Boussinesq (1885) [3] solution for stress propagation in an elastic material. It is a well-established model, which forms the foundation of multiple popular risk assessment models for soil compaction, such as SoilFlex (Keller et. al., 2007) [16]. Söhne (1953) [5] calculated the vertical stress under the center of a tractor tyre. The contact area, A, was divided into i small elements with an Area A_i each and a normal stress, σ_i, carrying the load $P_i = \sigma_i A_i$, which was treated as a point load. The vertical stress σ_z at a certain depth "z" was then calculated by summation accords Eqn (4):

$$\sigma_z = \sum_{i=}^{i=n}(\sigma_z)_i = \sum_{i=0}^{i=n}\frac{\upsilon P_i}{2\pi z_i^2}cos^{\upsilon+2}\theta_i \qquad Eqn(4)$$

Where, θ is the angle between the normal load vector and the position vector from the point load to the desired point, and υ is the concentration factor. For $\upsilon=3$, Eq. (4) satisfies the elastic theory of Boussinesq (1885) [3]. Hence, for a given loading condition, soil stress state becomes a function of the concentration factor υ. Fröhlich (1934) [4] stated that this concentration factor is empirical and has to be validated in (engineering) practice.

3 Results and discussion

3.1 Increase of vertical stress

Table 3. Results of measurements and calculation of the increase of vertical stress σ_z. (December 2nd 2019, after raining).

| No	Depth (m)	Vertical stress σ_z (kPa)		
		Load cell	Boussinesq Solution.	Söhne model.
1	0.15 m	182.62	183.27	180.26
2	0.30 m	68.48	67.07	65.89

On the field experimentation site, along the two wheeling events and using the tyre data listed in (Table 1), the increase of vertical stress in the soil profile was measured with the compression load cells at two depths specified (0.15 m and 0.30 m) and then, compared with calculations according to Eqn (1) and Eqn (4). Calculations with Söhne model were developed with a concentration factor of $\upsilon=3$ and yielded satisfactory predictions of stress propagation through soil. (Table 3) and (Table 4) shows a summary of the measurements and results obtained from the two wheeling events with the data registered and the calculations performed.

Table 4. Results of measurements and calculation of the increase of vertical stress σ_z. (January 29th 2020, sunny day).

No	Depth (m)	Vertical stress σ_z (kPa)		
		Load cell	Boussinesq Solution.	Söhne model.
1	0.15 m	171.21	177.35	174.62
2	0.30 m	59.07	63.92	62.78

3.1.1 Measurements and results comparison: Wheeling event after raining

(Fig 6) and (Fig 7) show a graphic comparison of the obtained results. The test was performed after raining, on December 2nd 2019. With Boussinesq solution, the calculated increase of vertical stress was over estimated within 0.4 % of the load cell measurements at 0.15 m depth and sub estimated within 2.1 % at 0.30 m depth. With Söhne model, the calculated increase of vertical stress was sub estimated within 1.3 % of the load cell measurement at 0.15 m depth and sub estimated within 3.9 % at 0.30 m depth.
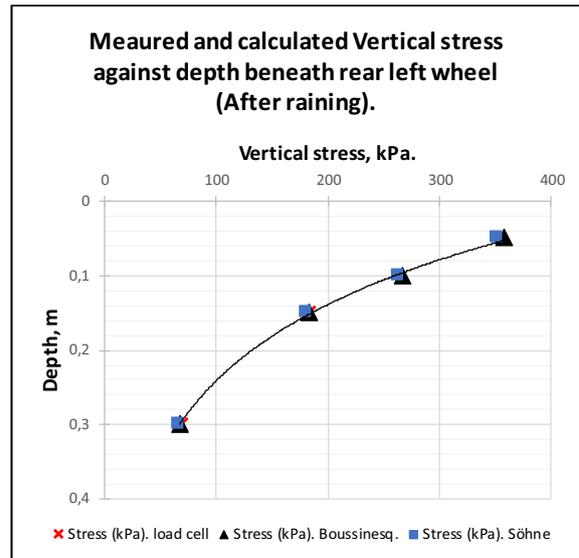
Fig. 6. Stress variation with soil depth: Measured increase of vertical stress (red crosses) for a tyre inflation pressure of 380 kPa (55 P.S.I.) and calculated according to the Boussinesq Solution (black triangles) and Söhne model (blue squares).
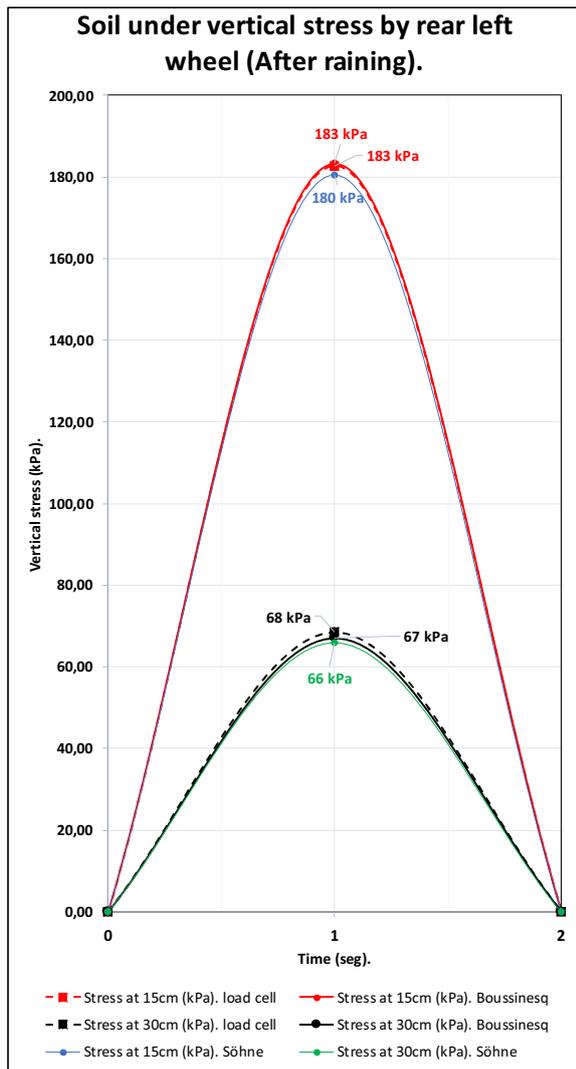
Fig. 7. Loading in the field: Measured increase of vertical stress (red and black broken curves) for a tyre inflation pressure of 380 kPa (55 P.S.I.) and calculated according to the Boussinesq solution (red and black solid curves) and Söhne model (blue and green solid curves).

3.1.2 Measurements and results comparison: wheeling event on a sunny day

(Fig. 8) and (Fig. 9) show a graphic comparison of the obtained results. The test was performed on a sunny day, on January 29th 2020. With Boussinesq solution, the calculated increase of vertical stress was over estimated within 3.5 % of load cell measurement at 0.15 m depth and 7.6 % over estimated at 0.30 m depth. With Söhne model, the calculated increase of vertical stress was over estimated within 2.0 % of the load cell measurement at 0.15 m depth and 6.0 % over estimated at 0.30 m depth.
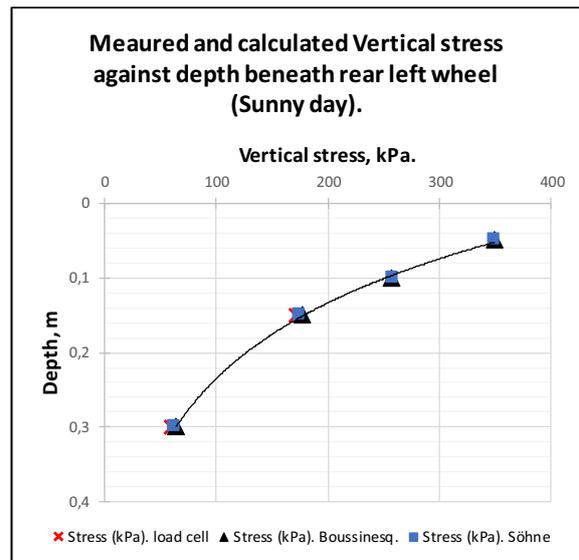

Fig. 8. Stress variation with soil depth (sunny day): Measured increase of vertical stress (red crosses) for a tyre inflation pressure of 380 kPa (55 P.S.I.) and calculated according to the Boussinesq Solution (black triangles) and Söhne model (blue squares).
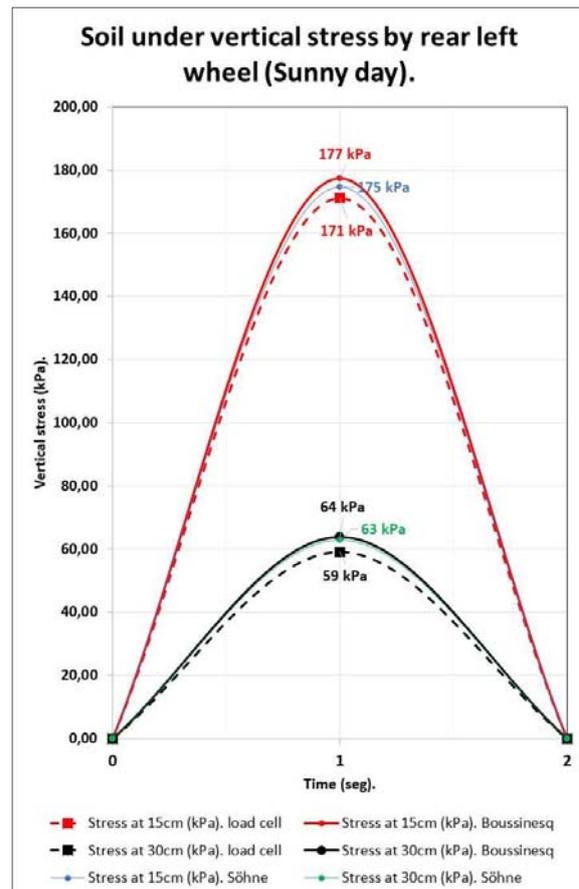

Fig. 9. Loading in the field (Sunny day): Measured increase of vertical stress (red and black broken curves) for a tyre inflation pressure of 380 kPa (55 P.S.I.) and calculated according to the Boussinesq solution (red and black solid curves) and Söhne model (blue and green solid curves).

Therefore, the obtain results from both vehicle tests and the load cells measurements were analyzed, it may be concluded that the compression load cells used provide adequate estimates of the increase of vertical stresses in soil, especially at 0.15 m depth. This is supported by the fact that measured values can be reproduced by the theoretical method.

3.2 Matric suction measurements and their effect on the increase of vertical stress

Monitoring of matric suction at 0.15 m and 0.30 m depths in the position indicated (Fig. 1), reported field measurements of matric suction less than 60 kPa. the values were registered in a field data registration set. After that, graphic sheets per depth were developed. (Fig. 10 and Fig. 11).
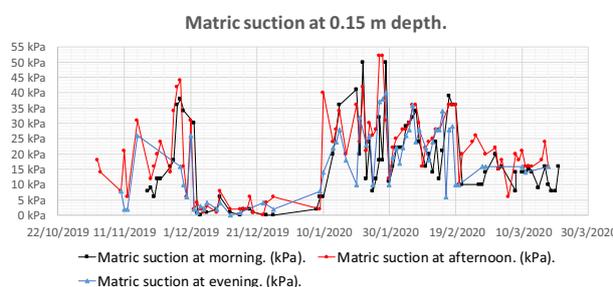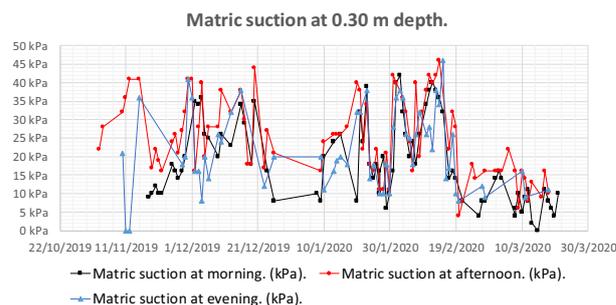

Fig. 10. Variation of matric suction with Jet Fill tensiometers at 0.15 m depth.
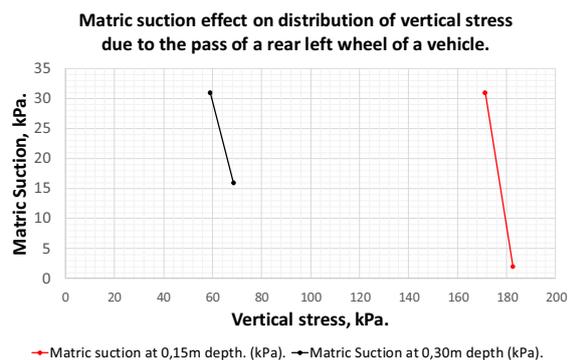

Fig. 11. Variation of matric suction with Jet Fill tensiometers at 0.30 m depth.

From this field data, according to the two wheeling events carried out on December 2nd 2019 and January 29th 2020, the measurements of matric suction registered in the two wheeling events were extracted, they are summarized in (table 4). (Table 4) shows the results obtained during the field measurements and laboratory tests (water content, increase of vertical stress with load cells, matric suction, saturation degree). The results show:

- The degree of saturation is a factor that affects the matric suction. If saturation degree is high (as the wheeling event after raining), matric suction is slow. If saturation degree is slow (as the wheeling event on a sunny day), matric suction is high.

Table 4. Measurements of Matric suction and increase of vertical stress, during the wheeling events, with laboratory tests results.

Depth (m).	Time	Gravimetric Water Content (w) (%).		Matric suction (s) (kPa).		Increase of Vertical Stress (σ_z) (kPa).		Porosity (n).		Saturation Degree (S) (%).	
		After raining Dec. 2nd 2019	Sunny day Jan 29th 2020	After raining Dec. 2nd 2019	Sunny day Jan 29th 2020	After raining Dec. 2nd 2019	Sunny day Jan 29th 2020	After raining Dec. 2nd 2019	Sunny day Jan 29th 2020	After raining Dec. 2nd 2019	Sunny day Jan 29th 2020
0.15	After-noon	18.89	8.11	2	31	182.62	171.21	0.435	0.378	64.94	35.34
0.30	After-noon	14.62	11.73	16	21	68.48	59.07	0.413	0.398	54.86	46.94

-Variation of matric suction have impact in the contact area between tyre and soil, which influence the increase of vertical stress: In the field test after raining the lower values of matric suction (2 kPa at 0.15 m and 16 kPa at 0.30 m) have influenced the increase of the contact area (386 cm^2) and consequently the increase of vertical stress (182.62 kPa at 0.15 m and 68.48 kPa at 0.30 m). Meanwhile, in the field test on a sunny day, the higher values of matric suction (31 kPa at 0.15 m and 21 kPa at 0.30 m) have influenced the reduction of the contact area (365 cm^2) and consequent reduction of the increase of vertical stress (171.21 kPa at 0.15 m and 59.07 kPa at 0.30 m).

The measurements of matric suction at two specified depths during the two wheeling events, show different lectures at the same depth, because they were performed in different conditions of water content. The differences between the measurements of matric suction at the same depth could be well explained: The test conducted on December 2nd 2019 was after raining and thus, the soil field was saturated (Saturation degree of 64.94 % at 0.15 m and 54.86 % at 0.30 m depth) and consequently the measurements of matric suction were low (2 kPa at 0.15 m depth and 16 kPa at 0.30 m depth). The test conducted on January 29th 2020 was on a sunny day (Saturation degree of 35.34 % at 0.15 m depth and 46.94 % at 0.30 m depth) and thus, matric suction measurements showed higher values (31 kPa at 0.15 m depth and 21 kPa at 0.30 m depth). (table 4).

Fig 12. Change in matric suction with vertical stress. Each point corresponds to soil suction measured during the two wheeling events.

(Fig. 12) represents the variation of matric suction on the two wheeling events. At 0.15 m depth, soil matric suction increases 29 kPa from the rainy day to the sunny day tests; As a result of suction rises, the increase of vertical stress in the soil profile reduces 11 kPa. At 0.30 m depth, soil matric suction increases 15 kPa and consequently, the increase of vertical stress decreases 9 kPa. Therefore, the measurements obtained during the two wheeling events show that, for a predetermined depth, a registered increase of matric suction because of the reduction of the contact area between the tyre and the soil surface, generate a consequent reduction in the increase of the vertical stress in the soil profile.

4 Conclusions

The present research concludes that, the vertical stress transmission measured in the soil profile with the compression load cells was not different from the Boussinesq analytic solution and the Söhne model. Analyzing the influence of the distribution: Stresses decrease with increasing distance from the soil surface. (i.e increasing soil depth).

A comparison of measured and simulated increase of vertical stresses, during wheel traffic in the two wheeling events carried out, show that the increase of vertical stresses, obtained from measurements through compression load cells, could be well predicted even with the classical elasticity theory based in Boussinesq (1885) [3] equations. In the present study, the use of a concentration factor of three ($v=3$) works well in the conditions of the field tests. Therefore, the obtained results support Keller's et. al. (2014) [12] and (2016) [13] researches.

The increase in the contact area between tyre and soil surface, as a result of lower matric suction, is the main reason for the increase of vertical stress. The reduction in the contact area, as a result of higher matric suction, is the main reason for the increase of vertical stress reduction.

In this research, the effect of soil matric suction on the increase of vertical stress in the soil profile has an inverse proportion: As matric suction increases, like

measurements from a rainy day to a sunny day, the increase of vertical stresses decreases but not in the same proportion as the matric suction.

New models for prediction of the contact stress distribution under agricultural tyres provide significantly improved input data for soil compaction models and therefore increase the accuracy of predictions of stresses in soil. This is of great importance for the prediction of soil compaction due to agricultural field traffic.

Acknowledgements

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