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Evaluation of soil compaction by modeling field vehicle traffic with SoilFlex during sugarcane harvest

N. Lozano *, M.M. Rolim, V.S. Oliveira, U.E. Tavares, E.M.R. Pedrosa

Universidade Federal Rural de Pernambuco (UFRPE), Programa de Pós-Graduação em Engenharia Agrícola. Rua Dom Manoel de Medeiros, s/n, Dois Irmãos – CEP: 52171-900 – Recife/PE, Brazil

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A B S T R A C T

Sugarcane harvest in Brazil involves infield traffic of trailers, haulout trucks and tractors, increasing the risk of soil compaction. Pseudo-analytic models have been used for analyzing soil compaction due to traffic as well as a tool to prevent it. The objective of this paper was to analyze the compaction process of an Ultisols in the costal table of Pernambuco, Brazil, subjected to vehicle traffic during sugarcane harvest. The pseudo-analytical model SoilFlex was used for modeling bulk density and soil moisture scenarios based on undisturbed soil samples taken at 0–0.1, 0.1–0.2, 0.2–0.3 and 0.3–0.4 m depth in a 120 m × 120 m area. Five bulk density scenarios, each one with four soil moisture conditions, were evaluated after passing vehicles during harvest: a loaded haulout truck, a loaded trailer hauled by a tractor and a loaded haulout truck hauling a loaded trailer. Soil vertical and pre-compression stresses showed that the haulout truck, as well as the trailer hauled by tractor, cause soil compaction beyond 0.2 m depth when the initial bulk density were 1.3, 1.4 and 1.5 g cm^{-3}.

1. Introduction

Brazil is the world's largest sugarcane producer with an increasing cultivated area of 8.4 millions of hectares (Conab, 2010). The crop is harvested either mechanically or manually harvested and transported from the field in haulout trucks and trailers that uses conventional road tyres. During the annual harvest the infield traffic is intense and sometimes occurs under inadequate soil moisture, increasing the risk of soil compaction (Raper and Kirby, 2006).

Haulout trucks axle loads are usually around 6 Mg in the front axle (single tyres) and 17 Mg in the rear tandem axle (with dual tyres). Sugarcane trailers (two axles with dual tyres) generally have 10 Mg load on both front and rear axles. These axle loads exceed the axle load limit (load on a single axle to 6 Mg and on a tandem axle unit to 8 Mg) proposed by Danfors (1994) to prevent superficial soil compaction. Previous soil compaction studies in sugarcane fields suggested that the decrease of crop productivity and bulk density increase were related to infield vehicle traffic (Kanali, 1997) and that the use of conventional tyres on haulout trucks may be causing additional soil compaction and consequently affecting sugarcane sprouting (Braunack, 2004). Braunack et al. (2006) suggested that vehicle traffic during sugarcane harvest in Australia have been affected crop production.

In Brazil, soil compaction is generally monitored throughout bulk density analysis and cone penetrometer test (Silva et al., 2009), however, these methods are not economically viable for big sugarcane areas. Alakukku et al. (2003) and Keller et al. (2004) suggested the use of pre-consolidation stresses as a soil compaction parameter to prevent additional soil compaction of agricultural soils.

The risk of compaction in agricultural soils depends among others on the mechanical stresses imposed by vehicle traffic (Arvidsson et al., 2011), therefore, knowing the magnitude and distribution of those stresses become a useful tool in soil compaction studies (Schjønning et al., 2008). Stresses transmitted by the vehicles tyres can be calculated using pseudo-analytical soil compaction models based on the approximation of Söhne (1953), which is based on the analytical equations for transmission of vertical stress developed by Boussinesq (1885) and adapted by Fröhlich (1934). Pseudo-analytical models generally use tyre inflation pressure, wheel load and dimensions as well as the vehicles characteristics as inputs. Soil parameters such as bulk density and soil moisture are used in the calculations of propagation and magnitude of stress. A detailed review on pseudo-analytical soil compaction models can be found in Défossez et al. (2003) and Keller and Lamandé (2010).

Thus, this study aimed to simulate the stresses transmitted to the soil by most frequent transport vehicles during sugarcane harvest using the SoilFlex model with different bulk densities and soil moisture conditions so that the results can be compared with

* Corresponding author. Tel.: +55 81 3320 6279; fax: +55 81 3320 6276.
E-mail address: nicolozan@hotmail.com (N. Lozano).

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pre-consolidation stresses to determine which vehicle is the best option to prevent soil compaction.

2. Material and methods

2.1. Area description

This study was conducted in the state of Pernambuco, Brazil (7°36′S, 35°00′W), in an area of 1 ha cultivated with sugarcane, third ratoon, row spacing 1.1 m. The soil was characterized according to the Brazilian soil classification system Embrapa (2006) as an Ultisol (59, 6 and 35% of sand, silt and clay, respectively). The soil's lower plastic limit is at water content of approximately 21% with a critical soil moisture of 15% and a maximum dry bulk density of 1.75 g cm^{-3} obtained by proctor test.

2.2. Vehicles

The vehicles considered in this work are the ones that drove over the experimental area during the year 2010 harvest. These vehicles consisted of (a) a haulout truck (Mercedes-Benz LS-2638) with tandem duals in the rear axle using Goodyear 11.00R22 152/149 tyres in both front and rear axles; (b) A two axles sugarcane trailer with dual wheels using Goodyear PLG8 10.00-20 146/143 tyres, and (c) A 4WD MF 650HD tractor to haul the sugarcane trailer on field. This tractor used Goodyear 14.9-26 10 Dyna Torq II tyres in the front axle and Goodyear 23.1-30 12 Dyna Torq II tyres in the rear axle. Wheel loads used to run the SoilFlex model were obtained from the maximum axle load authorized for public roads in Brazil, according to different wheel configurations, being these loads 6 and 17 Mg in the front and rear axles of the truck, respectively, and 10 Mg for each axle of the sugarcane trailer. The haulout tractor was simulated with a total weight of 7.350 kg distributed 40% in the front axle and 60% in the rear axle.

Tyre pressures were measured and corresponded to those suggested by the manufacturer's catalogs for the specific wheel load value, obtained by dividing the axle load by the number of wheels of each vehicle configuration. Wheels settings, wheel loads and tyre inflation pressures used for simulations are presented in Table 1.

2.3. Vertical stress simulation and bulk density variation

Vertical stresses transmitted to the soil during agricultural machinery traffic were calculated with the SoilFlex model (Keller et al., 2007). This model uses the analytical equations for vertical stress propagation developed by Boussinesq (1885) and Fröhlich (1934), and uses the approximation of Söhne (1953) for calculating normal stresses. The procedure used by Söhne (1953) to calculate the applied wheel load is to divide the contact area into small elements (i) each with an area A_i, in which an axial force is exerted σ_i, thus giving the point charges from $\sigma_i A_i = P_i$. Therefore, the vertical stress at a depth z is calculated by the Söhne (1953) approximation using Eq. (1):

$$\sigma_z = \sum_{i-0}^{i=n} \frac{\xi . P_i}{2\pi . r_i^2} \cos^{\xi-2}\theta_i \quad (1)$$

where ξ is the concentration factor defined by Fröhlich (1934), r is the distance from the load P to the desired point and θ the angle between the normal vector of the load and the position vector of the load. The concentration factors used for simulations correspond to those described by Défossez et al. (2003).

In SoilFlex, the contact stress distribution of vertical stress for all simulations was calculated with the contact area in the form of super-ellipse, according to Keller (2005). The inflation pressure of the tyres was adjusted to the values in Table 1. A gap between tyres of 10 and 12 cm was measured for dual wheels of the trailer and for the duals in tandem of the truck configuration, respectively. The distance between axels for the tandem configuration of the truck was 1.45 m.

The SoilFlex spreadsheet for vertical contact stress was modified to adjust the model to duals in tandem for the rear axle of the truck, since the model was originally designed for single wheels arranged in tandem axles. The modification was basically to model the wheels of the rear axle of the truck as single wheels in tandem with a distance between axles of 1.45 m and then copy and paste the result in the same worksheet at a distance equivalent to 12 cm (gap between wheels).

In the model, the front tyres of the truck were aligned with the external tyres of the duals in tandem configuration of the rear axle. For the tractor–trailer, the center of the tyres of the tractor was aligned with the midpoint between the dual wheels of the trailer. Soil mechanical parameters, as well as bulk density variation, where calculated according to O'Sullivan et al. (1999).

2.4. Soil compaction scenarios

Disturbed soil samples were collected in 12 points with 4 replicates in each point to determine soil moisture at 0–20 and 20–40 cm depth in December 2010 (dry season) during harvest operations of sugarcane. In July 2011 (rainy season) undisturbed soil samples were collected at the centerline between rows at 0–10, 10–20, 20–30 and 30–40 cm depths in four random points within the area each point with 4 replicates. From these undisturbed soil samples of bulk density in each depth samples were obtained the mean values of bulk density in each of the depth layers, as well as the mean values of soil moisture for each depth layer. From the obtained data five scenarios of bulk density were derived to model the stresses transmitted to the ground. The current measured soil bulk density was called scenario 3, considered as a hard soil. Scenarios 1 and 2 corresponded to firm soils, representing the beginning of the cultivation cycle right after tillage. Scenarios 4 and 5 corresponded to very hard soils, representing the soil at the end of the fifth year before sugarcane renewal. Soil classification as a firm, hard or very hard soil was in accordance with Défossez et al. (2003).

Each bulk density scenario was modeled using four moisture content conditions (Ua–d). Ua and Ud corresponded to measured moisture contents found in dry and wet seasons, respectively, and conditions Ub and Uc corresponded to intermediate moisture contents. Table 2 shows bulk density and moisture content combinations of simulated scenarios.

2.5. Pre-consolidation stresses

Pre-consolidation stresses were determined after loading using undisturbed soil samples collected at 0–20 and 20–40 cm depth

Table 1
Wheel loads and tyre inflation pressures.

Vehicle	Wheels settings[a]		Wheel loads (kg)		Recommended tyre pressure (kPa)	
	Front	Rear	Front	Rear	Front	Rear
Truck	s	td	3000	2125	655	517
Tractor	s	s	1635	2452	165	117
Trailer	d	d	2500	2500	724	724

[a] s, singles; d, duals; and td, duals in tandem.