Soil Stress State under Tractive Tire and Compaction Model

Prathuang Usaborisut, Dithaporn Thungsotanon

***Abstract*—**Soil compaction induced by a tractor towing trailer becomes a major problem associated to sugarcane productivity. Soil beneath the tractor's tire is not only under compressing stress but also shearing stress. Therefore, in order to help to understand such effects on soil, this research aimed to determine stress state in soil and predict compaction of soil under a tractive tire. The octahedral stress ratios under the tires were higher than one and much higher under higher draft forces. Moreover, the ratio was increasing with increase of number of tire's passage. Soil compaction model was developed using data acquired from triaxial tests. The model was then used to predict soil bulk density under tractive tire. The maximum error was about 4% at 15 cm depth under lower draft force and tended to increase with depth and draft force. At depth of 30 cm and under higher draft force, the maximum error was about 16%.

***Keywords*—**Draft force, soil compaction model, stress state, tractive tire.

I. Introduction

AGRICULTURAL machinery causes severe negative effects on soil compaction, especially during harvesting process. Bailey and Johnson [1] said that the interest in soil compaction has increased recently with the increase in size of field machines and their potential for causing adverse soil compaction. In Thailand, use of a tractor towing trailer for transporting sugarcane in a field and to a factory becomes more common due to advantage of working on moist soil. Soil has to bear loads from trailer, sugarcane, and tractor which are all transferred into the soil through wheels. Although high axle load increases the risk of soil compaction, it can improve tractive performance [2]. In practice, a farmer sometimes uses a tractor with a semi-trailer to carry sugarcane up to 60 t. Abu-Hamdeh and Reeder [3] found that the soils on which loads were applied did not only compact but also slid in other directions due to shearing. Many researchers have studied soil compaction process by measuring the soil stress state since it can reflect causes of soil compaction [4]-[6]. The development of models that adequately describe soil compaction has also been studied. Bailey et al. [7] presented a model for the soil compaction by a hydrostatic stress. Grisso et al. [8] studied the effect of shearing stress on soil compaction and changed the hydrostatic stress to the octahedral normal stress, but the coefficients were still determined from hydrostatic tests. Bailey and Johnson [1] developed soil compaction model by adding octahedral shear stress. Research on soil compaction is important as soil compaction itself depends on the soil type, the soil condition and the characteristics of the vehicle traffic [9]. The objectives of this research were to clarify the stress state induced by tractive tire and to develop a soil compaction model to predict bulk density obtained under such stress state.

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II. Methodology

Soil used in the experiment was sandy loam soil (64.56% sand, 17.11% silt, and 18.33% clay) taken from the sugarcane field. The soil was air-dried and sieved with 2-mm sieve. Then, water was added to obtained soil moisture content of 12%db and leave overnight for equilibrium. The soil was filled into an 80×240×60 cm^3 soil bin (Fig. 1) and compacted to have an initial bulk density of 1.4 g/cm^3. The stress state transducers (SST) were buried in soil at 15 and 30 cm depth at center of tire path. The tire moved over the SST in a specific direction (Fig. 2) referring to the research of Bakker et al. [10]. The KUMHO 5.00-12 4PR rubber tire was set for carrying total vertical load of 1,373.4 N corresponding to contact pressure in the field. A three-phase motor was a main power source to drive the tire with a forward speed of 0.5 km/h. Two draft forces were applied to a frame of the tire set using dead weights of 245.25 N and 735.75 N. Soils in the bin were sampled by core samplers for dry bulk density and moisture content at the depth of 15 and 30 cm. Penetration resistances were determined by cone penetrometer. During the tire moved, the dynamic stress signals were recorded with a sampling rate of 10 Hz [11]. An acquisition system consisted of the NI-9205 and cDAQ 9191 WIFI receiver, LabView 2014 software to record, monitor, and process the signal from the SST. After the tire passed, bulk density and penetration resistance were measured at the center of the tire rut.

The compaction data for use in the model development were acquired from triaxial tests. The sample preparation, measurements, data acquisition, testing sequence and model development followed the detail described by Bailey and Johnson [1]. The initial hydrostatic stress was set to one of three predetermined levels of 300, 400, or 500 kPa.

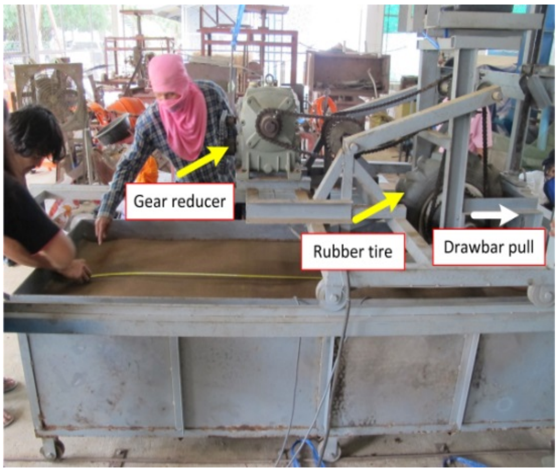

Fig. 1 Soil bin and the wheel drive system

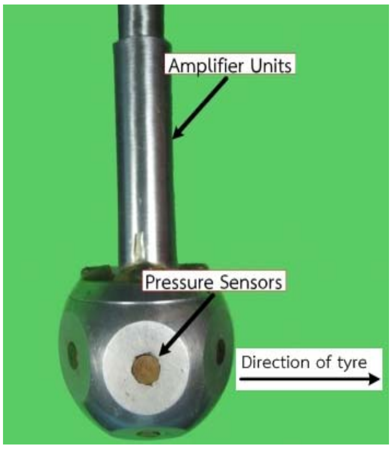

Fig. 2 The stress state transducer (SST)

III. Results

As a tractive tire approached the SST, the stress components gradually increased in magnitudes and reached their highest when tire axle located above the SST and decreased to nearly zero when the tire passed over. The octahedral stresses calculated from principle stresses at depth of 30 cm for draft forces of 245.25 N and 735.75 N show in Figs. 3 and 4, respectively. Both octahedral stresses increased up to their maximum values and decreased afterward However, the value of octahedral normal stresses were all time lower than the octahedral shear stresses for both draft forces cases. The octahedral stress ratios (OSR = τ_{oct}/σ_{oct}) at peak, under tractive tires with draft forces of 245.25 N and 735.75 N were 1.47 and 1.69, respectively. These values of OSR confirmed that the soil under the tire would be distorted and compacted [12]. The value of OSR tended to increase with tire's passage number as shown in Fig. 5. High value of OSR may be affected by shear force generated by tractive tire as indicated by higher value of OSR under higher daft force of 735.75 N compared to lower draft force of 245.25 N. However, Bailey et al. [7] reported that the soil under the tire is probably failing in shear at high OSR even though little or no net traction was being developed by the tire.

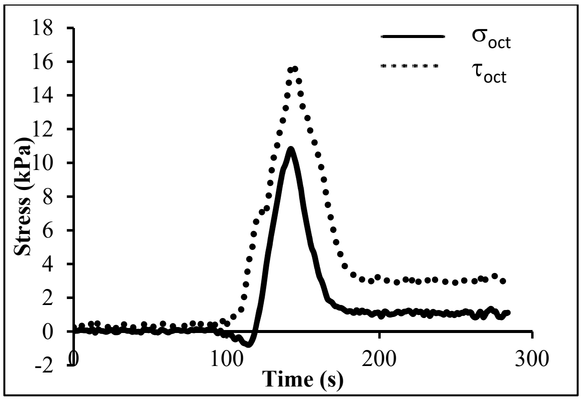

Fig. 3 Octahedral stress (σ_{oct} and τ_{oct}) of the first passage at 30 cm depth under 245.25 N draft force

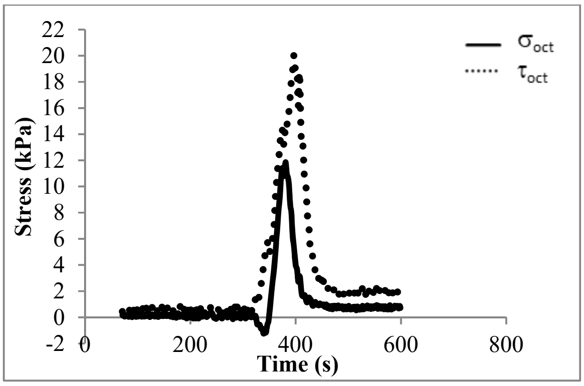

Fig. 4 Octahedral stress (σ_{oct} and τ_{oct}) of the first passage at 30 cm depth under 735.75 N draft force

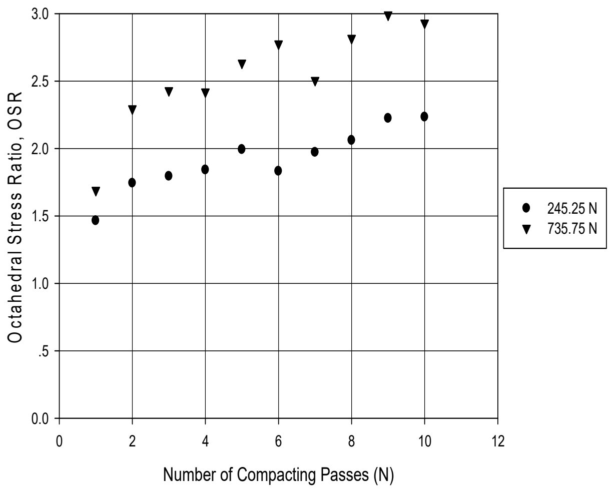

Fig. 5 Peak octahedral stress ratios at 30 cm depth with numbers of passages

Soil under tractive tire in both stress state condition was changed in its physical property. Bulk density serving as soil compaction indices increased with increases of number of tire passage and draft force. The bulk density of low draft force of 245.25 N at depth of 15 cm increased significantly by 7.94% and 22.02% at the first and the tenth passages, respectively. At high draft force of 735.75 N on the same condition, the bulk density increased significantly by 11.89% and 21.68%, respectively. The tire slips under 245.25 N draft force were about 11.42% for all numbers of passage.

The datasets acquired from triaxial tests at constant octahedral normal stresses of 300, 400 or 500 kPa were used in modeling soil compaction. The compaction model expressed in (1) was determined by multiple non-linear regressions. The final estimated bulk density (BD_{est}) was an exponential function of initial bulk density (BD_i), octahedral normal stress (σ_{oct}), octahedral shear stress (τ_{oct}) and a set of coefficients (A, B, C and D). The three coefficients A, B and C were linear relation with initial bulk density, while the coefficient D was a function of both initial bulk density and octahedral normal stress.

$$BD_{est} = e^{\left\langle \ln(BD_i) - \left\{ (A + B\times\sigma_{oct})\left(1 - e^{(-C\times\sigma_{oct})}\right) + D(\tau_{oct}/\sigma_{oct}) \right\} \right\rangle} \quad (1)$$

$$A = -0.034 + 0.0212 BD_i, \qquad \left(r^2 = 0.9516\right) \quad (2)$$

$$B = 0.00006 - 0.00004 BD_i, \qquad \left(r^2 = 0.8135\right) \quad (1)$$

$$C = 0.3184 + 0.4565 BD_i, \qquad \left(r^2 = 0.9819\right) \quad (4)$$

$$D = -0.957 + 0.0002\sigma_{oct} + 1.362 BD_i - 0.0001217\sigma_{oct} \times BD_i - 0.4947 BD_i^2, \qquad \left(r^2 = 0.8347\right) \quad (5)$$

where BD_{est} = final estimated bulk density, g/cm^3, BD_i = initial bulk density, g/cm^3, σ_{oct} = octahedral normal stress, kPa, τ_{oct} = octahedral shear stress, kPa, A, B, C, D = compactibility coefficients

Table I lists the measured value of bulk density of soil in soil bin under tractive tire and predicted value of bulk density by using (1). The predicted values quite closed to measured values in case of lower draft force of 245.25 N and at 15 cm depth. The percent of error which was calculated between each predicted and measured bulk density showed its minimum value of 0.01% at the third compaction pass and its maximum value of 4.20% at the first pass. At deeper soil layer of 30 cm depth with the same draft force, the error increased with its maximum of 12.18%. When draft force increased to 735.75 N, the error increased in both layer compared to the same depth layer of 245.25 N. The most maximum error in the test was 16.44% found in case of 735.75 N draft force at 30 cm depth.

The compaction model was developed to describe the compaction of triaxial soil samples under cylindrical stress loading. Bailey and Johnson [1] reported that the predicted and measured bulk densities were in close agreement. Maximum errors were found only between -4 and +4%. In this research, the developed model was used to predict the compaction under tractive tire. Error in 15 cm depth under lower daft force condition was close to that reported from Bailay and Johnson [1] but it was much higher in other conditions.

TABLE I
MEASURED AND PREDICTED DRY BULK DENSITIES OF SOIL AFTER PASSAGES OF TRACTIVE TIRE

Drawbar Pull (N)	Depth (cm)	Bulk Density (g/cm^3)	Compaction Pass (N) 1	2	3	5	10
245.25	15	BD_{real}	1.495	1.55	1.56	1.62	1.69
		$BD_{predict}$	1.432	1.493	1.560	1.634	1.712
		Error (%)	4.196	3.621	0.012	0.895	1.357
	30	BD_{real}	1.425	1.45	1.42	1.475	1.52
		$BD_{predict}$	1.441	1.497	1.557	1.625	1.705
		Error (%)	1.157	3.279	9.672	10.221	12.178
735.25	15	BD_{real}	1.60	1.595	1.670	1.670	1.740
		$BD_{predict}$	1.480	1.547	1.633	1.712	1.802
		Error (%)	7.472	2.958	2.184	2.536	3.592
	30	BD_{real}	1.485	1.52	1.49	1.535	1.545
		$BD_{predict}$	1.445	1.518	1.599	1.691	1.798
		Error (%)	2.639	0.084	7.350	10.186	16.435

IV. CONCLUSION

Developed prediction model of soil compaction in the shallow depth was quite applicable. At greater depth, loads may be quite small to play a major role of compacting soil. Future work should be done on the effect of normal load on the prediction model to evaluate effectiveness of the model in predicting soil compaction in deeper soil layer.

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