Modelling Soil Physical Properties for Environmental Protection

✉**Ajayi, Ayodele Ebenezer** [1,2]

[1] *Soil, Water and Environment Division, Department of Agricultural Engineering, Federal University of Technology, PMB 704, Akure, Ondo State, Nigeria*
[2] *Soil Science Department, Federal University of Lavras, PO Box 3037, MG, 37.200-000, Lavras, Brasil.*
✉*Correspondence: ayo.ajayi@gmail.com*

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Abstract
The degradation of soil structure in mechanised agriculture has been widely recognized as a major threat to sustainable food production and the environment. Whereas biological and chemical degradation in soil could be easily assessed from temporal analyses of relevant factors, the assessment of physical degradation in soil is contentious except in eroded area. In this study, we present the application of load bearing capacity model developed from soil precompression stress as a technique for assessing degradation in soil structure. The model was applied to estimate the load bearing capacities of soils sample collected in Brazil and Nigeria. It was also applied in estimating the permissible pressure on soil at different profiles as well as in evaluating the effect of traffic frequency and the efficiency of mitigation strategies. The results from this study showed that the use of the Load Bearing Capacity models developed from representative soil sample, when used with the precompression stresses determined after traffic allowed an accurate estimation of the compressive responses of the soil. Application in traffic study showed that compaction susceptibility increase with increasing traffic intensity, while mitigation strategies involving the use of forest residue reduces the extent of compaction in forestry operation. It is therefore concluded that appropriate use of the precompression stresses data of soils will assist as a decision support tool in the planning of the mechanized agriculture and forestry operations in order to avoid soil structure degradation and the consequent environmental damage.

Key words: *soil structure, soil compaction, degradation, precompression stress, environmental damage.*

Introduction

Worldwide, in other to cope with increasing population and climatic variability, there is an increasing demand for higher productivity per unit land area. Meeting this demand often bore down to increased mechanisation of the agricultural production processes, necessitating sometimes increase in tractor size and implement weight (Horn and Fleige 2003; Kirkby, 2007), increased cropping cycles with consequent higher traffic frequency and intense soil loading among others (Horn and Fleige 2003; Alakuku *et al.*, 2003). These activities have been noted to increase susceptibility of soil to compaction, promote the degradation of soil structure and thereby constituting threats to sustainable agricultural production and the environment.

Soils tend to compact when submitted to pressure above its inert strength either statically or dynamically (Peth *et al.*, 2006; Keller and Lamandé, 2010). Soil compaction harmfully affects many properties relevant to soil stability, moisture dynamics and crop growth. Compaction increases the bulk density of the soil, modifies pore geometry (size and continuity of pores), altering air permeability and saturated hydraulic conductivity (Kirby, 2007; Ball and Robertson, 1994; Dias Junior *et al.*, 1999). The changes in physical and hydrological properties of the soil affect soil-structure-dependent redox potential, water and nutrient transport processes and changes the biological activity of the soil flora and fauna (Brussaard and Van Faassen, 1994; Bouwman and Arts, 2000), leading to poor yield from farms, increased power requirement for tillage and poor environmental condition (Soane and van Ouwerkerk, 1995; Horn and Rostek, 2000; Canillas and Salokhe, 2002; Dauda and Samari, 2002; Peth *et al.*, 2006).

Whereas biological and chemical degradation in soil could be easily assessed from temporal analyses of relevant factors, the assessment of physical degradation in soil is contentious except in eroded area. There is however consensus in literature on the use of precompression pressure to evaluate inert strength and stability of the soil, following its adaptation in agricultural soil mechanics (Horn 1981;Dias Junior and Pierce, 1995; Ajayi *et al.*, 2009; 2011). The precompression stress is obtained from the soil compression curves (Figure 1), which shows the relationship between applied stress and strain response in the soil sample (Casagrande, 1936; Holtz and Kovacs, 1981). The precompression stress divides the curve into a region of elastic (recoverable deformation) and plastic (unrecoverable deformation)(Holtz and Kovacs, 1981; Canarache *et al.*, 2000), and is therefore an indicator of the maximum stress previously sustained by a soil (Dias Junior and Pierce, 1995; Defossez and Richard, 2002) and an indicator of its inner strength (Arvidsson, 2001). In agriculture and forestry operations, the precompression stress could be used to prevent soil degradation (Gupta *et al.*, 1989; Lebert and Horn, 1991; Krümmelbein *et al.*, 2009). However delineating the point and the scale of observation to show that the soil is degrading or already degraded requireaccurate diagnostic tool that could detect changes in soil physical properties. This study aims to models soil precompression stress as a tool for evaluating changes in soil quality index in soil degradation study.

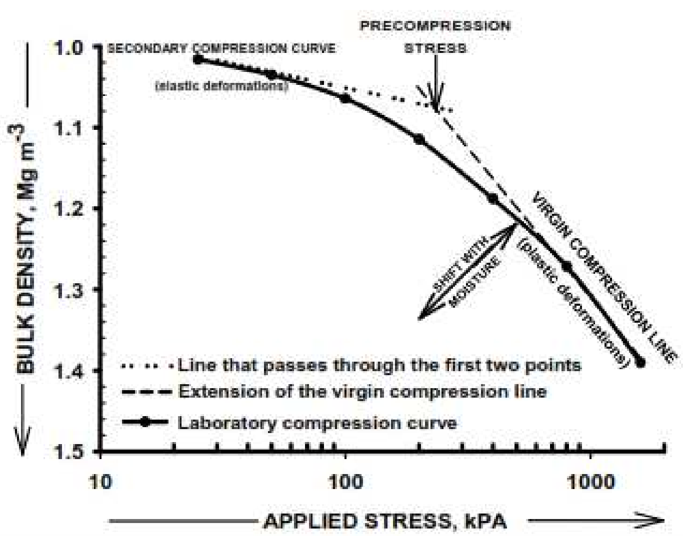

Figure 1: Soil Compression Curve illustrating the position of the precompression stress

Materials and Method

Soil samples from the A and B horizon were collected from Brazil and Nigeria covering different soil and land use types. These samples were collected in 6.5 cm x 2.5 cm aluminium rings using Uhland undisturbed soil core sampler. At each sampling point, the sampling device was pushed carefully into the soil using a falling weight and the ring filled with soil was removed from the sampler, wrapped with plastic materials and paraffin wax to preserve field moisture level. In the laboratory, each sample is carefully trimmed to the size of their respective rings. Part of the scrapped soils was used to determine the field moisture contents of the samples, which was the used in moisture adjustment for the model construction. The remaining scraped soils for each site were air-dried and sieved (<2 mm) for other standardized tests. Textural classification was performed according to Brazilian standard procedures described in Embrapa (1997). Particle size distribution was determined using the pipette method after dispersing with 1N NaOH. Particle density was determined using 95% hydrated alcohol with 20 g of air-dried soil material in a 50-ml pycnometer (Blake and Hartge, 1986).

Selected samples in replicates from each site were equilibrated to tension between saturation and wilting point using pressure table or pressure chambers. These samples were used for confined uniaxial compression test. For the test, the soil core held within the coring cylinder placed in compression cell was submitted to pressures of 25, 50, 100, 200, 400, 800 and 1600 kPa in step - by – step using sets of pneumatic S-450 Terraload floating ring consolidometer (Durham Geo Enterprises, USA). Each pressure step was applied until 90% of the maximum deformation was attained and then the pressure is increased to the next level. The 90% of maximum deformation was determined by drawing a straight line through the data points of the initial part of the curve obtained when dial readings were plotted versus square root of the time, until this line intercepts the y axis (dial readings). A second straight line was drawn from this intersection with all abscissas 1.15 times as large as corresponding values on the first line. The intersection of this second line and the laboratory curve is the point corresponding to 90% consolidation (Taylor, 1948; Asssouline et al., 1997). The applied pressure versus deformation data were used to construct the soil compression curves, from which the preconsolidation pressures (σp) were determined following the procedure of Dias Junior and Pierce (1995). The pre-consolidation pressures values were thereafter plotted against the soil water potential or moisture content and regression line fitted from a function in the form $\sigma_p = a + b \ln \Psi_m$(Oliveira et al., 2003) for potential based or $\sigma_p = 10^{a + bU}$ for the moisture content based. The regression line is the bearing capacity model (LBC) of the soils under study. It represents the adjustment of preconsolidation pressures to varying water matric potential or water content. The regression analyses were accomplished using the software Sigma Plot 10.0 (Jandel Scientific).

Results and Discussions

Figure 2 present the load bearing capacity model (LBC) for samples collected from Rio Doce MG, Brazil presented as functions of matric potential and volumetric water content. The soil load bearing capacity has been defined as the capability of a soil structure to withstand stresses induced by field traffic without changes in the three-dimensional arrangement of its constituent soil particles (Alakukku *et al.*, 2003). The soil LBC models represents mathematically the relationship between soil volumetric water content (θ) and soil precompression stress (σp) and may be described by the Equations $\sigma_p = 10^{a + bU}$ **or** $\sigma_p = a + b \ln \Psi_m$(Dias Junior, 1994). In the model for the siets, the precompression stress decreases exponentially with the increases in the volumetric soil water content as expected and the estimated linear "a" and angular "b" coefficients varies. In both cases the permissible pressure at specific moisture status without degrading the soil could be easily established from the LBC model curve. In first case, the soil could sustain a vertical pressure of 220kPa at 100kPa matric potential without degrading the soil structure, while in the second case, the soil could support a vertical load of 316kPa at 0.2 m^3m^{-3} without deforming it.

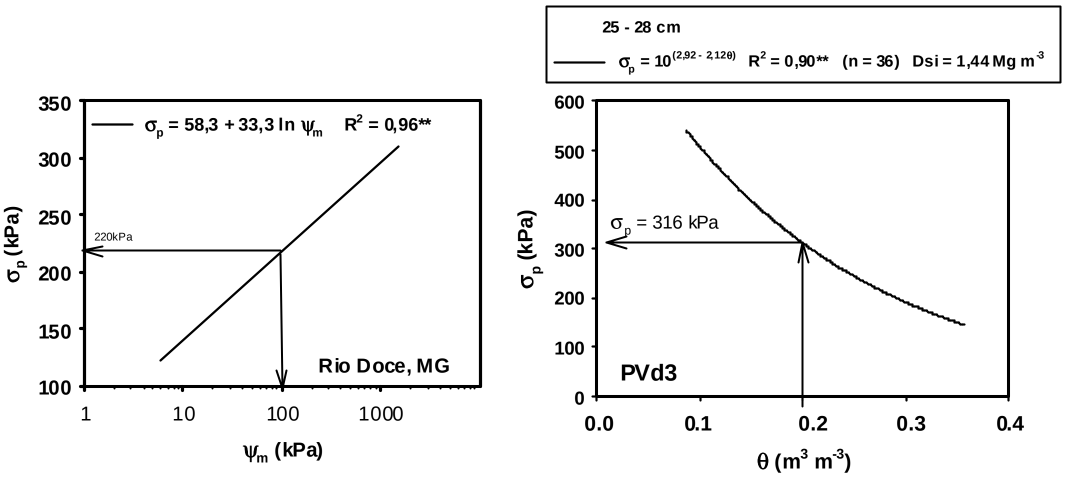

Figure 2: Estimation of the maximum pressure that should be applied to the soil in order to avoid soil compaction using the Load Bearing Capacity model.

In the traffic of agricultural equipment and machinery during field operations, pressures are applied depending on the weight of the equipment and the contact area with the soil. The pressure is transmitted as stresses in the soil profile with consequent chain of cause and effect depending on the load bearing capacity of the soil. The LBC had been shown to be largely dependent on a number on intrinsic and management factors including the soil mineralogy, traffic history and moisture status (Ajayi *et al.* 2009; Keller and Lamandé, 2010; Lamande and Schjønning, 2011). Whereas the intrinsic soil factors may be out of farmer's control, the LBC models allow the moderation of the management factors in avoiding soil degradation and the associated environmental damages. Thus, with the LBC, the size of the implement, the type of surface contact (track or tyres), the operational pressure in tyres, the frequency of traffic and possible delay times as well as the optimum operating moisture condition in the soil could be properly planned ahead of field operation.

The load bearing capacities of soils may vary at different depths or profile, thereby making the control of the management factors more cumbersome. To highlight the possible variation in the abilities of soils to sustain pressure without degradation along the soil profile, the samples collected from the A and B horizons at Lavras MG, Brazil and Ire Ekiti, Nigeria were used. Figure 3 present the LBC models of the A and B-horizon for the sites. At Lavras MG the A horizon had higher LBC curve than the B horizon, while at Ire Ekiti, the B horizon's curve was higher. The result highlights the import of organic matter on the strength of soils. Although both soil sample under native forest condition, organic matter content were higher in the A horizon, of the Ire Ekiti (Ajayi *et al.*, 2011), lowering its strength.

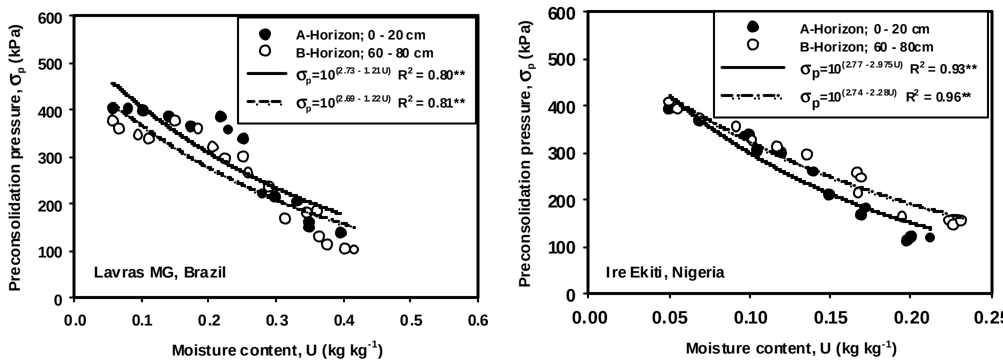

Figure 3: Load Bearing Capacity Model for the A and B horizons of Lavras MG, Brazil and Ire Ekiti, Nigeria.

In determining that pressure that could be applied on the soil without degrading the A or B-Horizon of the sites, the procedure of Snedecor and Cochran, (1989) was applied to test the homogeneity of the load bearing capacity models of the 2 horizons at each site. The tests showed that at both sites, the bearing capacity models for the 2 sample depths were homogenous (Table 1), implying that a single bearing capacity model combining the A and B horizons dataset for each site could then be generated (Figure 4). In spite of the homogeneity of the 2 horizon at both sites, the linear “a” and angular “b” coefficients at Ire Ekiti were significant at 1% probability level, implying some differences in the certain characteristics of the soil at the 2 profiles. This behaviour reflects the soil type at both sites. In Lavars MG, the soil was Oxisols, noted with having uniform soil along its profile due to long weathering history while at Ire Ekiti, the soil type was Inceptisols associated with horizontal differentiation (Curi and Franzmeier, 1984). Another factor was the land use type;native forest which ensure minimal disturbance of the soil at both sites.

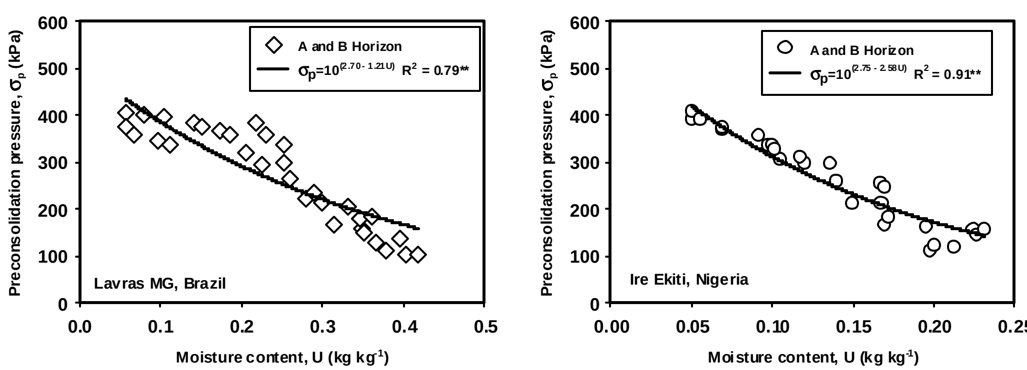

Figure 4: Representative Load Bearing Capacity Model for both Site following Homogeneity test.

Table 1: Comparison of the load bearing capacity models for homogeneity of the samples from Ire Ekiti Nigeria and Lavras MG Brazil A and B horizons.

Site Label	F	F	
		Angular Coefficient, *b*	Intercept of Regression, *a*
Lavras A vs Lavras B	Homogenous	Ns	ns
Ire Ekiti A vs Ire Ekiti B	Homogenous	**	**

*** significant at 1 % probability level; ns: not significant*

In soils with homogenous LBC, the representative LBC could then be used in equipment selection. However, in soil with non-homogenous LBC at the 2 horizons, it may be critical to examine the depth of operation of the equipment and the stress transmission profile in order to determine appropriate loading that would not degrade the soil, most especially the sub soil (Kondo and Dias Junior, 1999; Silva *et al.*, 1999).

The LBC models can also be used to evaluate the effect of traffic intensity on the soil structure. To accomplish this, the LBC of the soil under investigation would be divided into 3 distinct regions (Figure 5). Region "a" – this is the region in wherein the precompression stresses determined after the trafficking of the soils are higher than the upper limit of the 95% confidence interval of the LBC model. This region is considered as the one where soil compaction had already happened. Region "b" - this is the region where the precompression stresses determined after trafficking of the soils lies between the upper and the lower limit LBC model 95% confidence interval for the soil under study. Stress application within thisregion will not causesoilcompaction, but the region represent areas with high susceptibility to soil compaction in in future unregulated mechanisation. Region – "c" – a region where the precompression stresses determined after trafficking of the soils are lower than the lower limit of the 95% confidence of the LBC model. In this region, there is no soil compaction and susceptibility is very low.

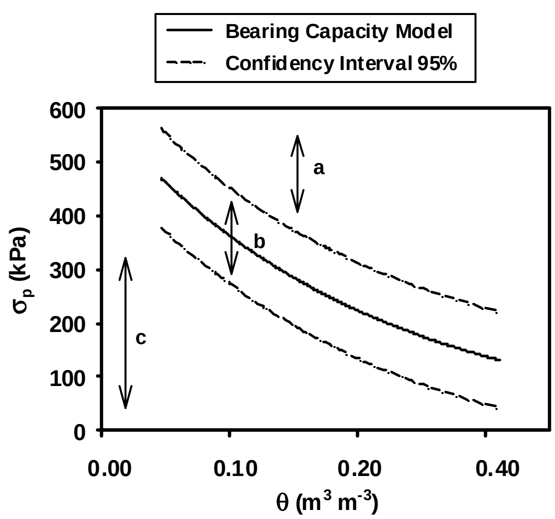

Figure 5. LBC model divided into regions (a), (b) and (c) used in the analysis of the effects of traffic on soil structure.

This method was applied in assessing the consequence of repeated wood transportation on the structure of a Yellow Ultisols from an Eucalyptus Farm (Peçanha MG, Brazil). The harvested woods were transported witha tyre-type Forwarder. Using the criteria earlier presented (Figure 5), the consequences of the repeated trafficking were investigated at the20 cm depth, using 25, 50 and 100% of the collectedsamples after8, 16and40Nospasses of the Forwarderrespectively(Figure 6). The resultsindicated thatsoil compactionincreased with depth as the traffic intensity increases (depicted by the number of passes) of the tyre type Forwarder.

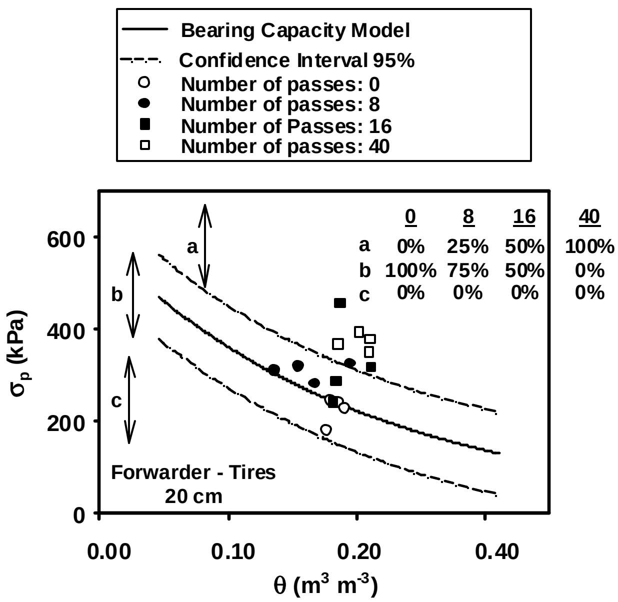

Figure 6:Assessment of the effect of different No of passes of Forwarder with tires on precompression stress of a Yellow Ultisols using Load Bearing Capacity model.

The LBC model can also be used to evaluate the efficiencyof mitigation strategies in reducing the effect of applied pressure. In this study, the impact of the use of forest residue in theattenuationof the applied pressure byaForwarder,loaded with9m^3 of wood, when the Forwarder passed 2 and 8 timesonthe sametraffic lane was evaluated. The experiment was conducted on a Yellow Oxisol from RioDoce, MG Brazil. Brushwood andeucalyptusbark were spread on the soil surface to prevent the direct contact of the Forwarder tyres with the soil surface. Using the defined criteria (Figure 5), it was observed that soil compaction was attenuated, particularly when brushwood and bark (GC) was used. Direct trafficking on the soil without residue (SR) resulted in the worse compaction condition in the study. It was also observed that as traffic intensity increased from 2 to 8 times, the extent of soil compaction increased(Table 2).

Table 2 Percentage of compacted soil samples evaluated with the defined criteria, after 2 and 8 passes of a loaded Forwarder on different surface conditioning using forest residue

	Type of Soil Surface Conditioner / No. of Passes of the Forwarde		
	2 passes of Forwarder		
	---------- (%) ----------		
Compacted samples	GC	G	SR
	0	0	5
	8 passes of Forwarder		
	-------- (%) --------		
Compacted samples	GC	G	SR
	5	15	70

GC = brushwood and bark; G = brushwood; SR = without residue.

Conclusions

Soil degradation is a multidisciplinary subject with consequence on food and fibre production as well as environmental sustainability. This study establishes a universal evaluation criterion for compaction which is the most degenerative form of soil degradation. The application of the LBC models on selected tropical soils as discussed in this study showed that the recovery of compacted areas, if possible, requires a very long time and could be very expensive; therefore, the most appropriate way to avoid this problem and its consequence would be its prevention. Thus, the development of models that allow us to predict susceptibility or otherwise to soil compaction of various field activities would be very useful in the agriculture and environmental studies.

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