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BEARING CAPACITY MODEL RELATED TO SOIL STRUCTURE SUSTAINABILITY

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Introduction:

One of the limitations to reach sustainable soil management is related to soil strength, which can be natural or due to the inadequate soil management.

Different soil management has been altering the physical and mechanical soil properties (Barnes et al., 1971; Gupta et al., 1985; Larson et al., 1989; Soane and van Ouwerkerk, 1994; Dias Junior and Pierce, 1996ab, Dias Junior and Miranda, 2000, Horn et al., 2000; Dias Junior, 2000), causing soil structure degradation and restricting root penetration due to the insufficient root turgor pressure to overcome the soil mechanical resistance (Gysi, 2001).

Soil structure degradation may be characterized by an increase in the soil bulk density and soil strength (Dias Junior et al., 1999); a decrease in the total porosity, size and continuity of the pores (Hillel, 1982; Servadio et al., 2001) and may limit nutrient uptake, water infiltration and redistribution, gas exchange, seedling emergency and root development (Tardieu, 1988; Smucker and Erickson, 1989; Bicki and Siemens, 1991; Dürr and Aubertot, 2000, Arvidsson, 2001; Ishaq et al., 2001) resulting in decreased yields (Arvidsson, 2001; Radford et al., 2001; Dauda and Samari, 2002), increased erosion and increased power requirement for tillage (Stone, 1987, Canillas and Salokhe, 2002).

The soil compression curves obtained from laboratory uniaxial compression test are frequently used in soil compressibility studies (Larson et al., 1980; Larson and Gupta, 1980; Bingner and Wells, 1992; O'Sullivan, 1992; MacNabb and Boersma, 1993; Dias Junior, 1994; Dias Junior and Pierce, 1996ab; Canarache et al., 2000). These curves describe the relationship between the logarithm of the applied pressure and bulk density or void ratio (Casagrande, 1936; Leonards, 1962; Holtz and Kovacs, 1981). The precompression stress is the pressure that divides the soil compression curves into a region of small, elastic and recoverable deformation (secondary compression curve) and a region of plastic and unrecoverable deformation (virgin compression curve) (Holtz and Kovacs, 1981; Jamiolkowski et al., 1985; Dias Junior and Pierce, 1995; Canarache et al., 2000). Thus, the precompression stress is an indicator of the maximum previously stress sustained by a soil (Holtz and Kovacs, 1981, Dias Junior and Pierce, 1995; Defossez and Richard, 2002) and also an indicator of the soil strength (Arvidsson, 2001). Thus, in agriculture, application of stress greater than the precompression stress should be avoid in order to avoid unrecoverable soil deformation (Gupta et al., 1989; Lebert and Horn, 1991; Defossez and Richard, 2002).

The precompression stress depends on several factors such as: changes in the total stress due to erosion and excavations, wetting and drying processes, soil texture, structure, and bulk density, soil management, organic matter, chemical alterations due to the weathering, precipitations, pH, ions exchange, etc. (Casagrande, 1936; Schmertmann, 1955; Crawford, 1964; Brumund et al., 1976; Holtz and Kovacs, 1981; Horn, 1988; Jose et al., 1989; Dias Junior and Pierce, 1995; McBride and Joosse, 1996, Veenhof and McBride, 1996; Kondo and Dias Junior, 1999; Silva et al., 1999 and other).

Methods for estimation of the precompression stress are available in the literature (Casagrande, 1936; Burmister, 1951; Schmertmann, 1955; Sällfors, 1975; Anderson and Lukas, 1981; Culley and Larson, 1987; Jose et al., 1989; Lebert and Horn, 1991; Dias Junior and Pierce, 1995; Veenhof and McBride, 1996 and McBride and Joosse, 1996). Thus, the use of precompression stress in the agriculture studies is consolidated.

Considering that the precompression stress is an indication of the soil strength (Arvidsson, 2001), of the maximum stress that should be applied to a soil in order to avoid soil structure degradation (Gupta et al., 1989; Lebert and Horn, 1991; Defossez and Richard, 2002), of the soil structure sustainability (Dias Junior et al., 1999) and a reduction in the precompression stress values may be used as an indicator of soil structure recover, the Bearing Capacity Model, which is the adjustment of the precompression stress as a function of volumetric water content or suction, may be used also to detected the soil structure changes trough time due to the different soil management.

In addition, the Bearing Capacity Model has different uses in agriculture and for environment quality studies, such as: a) to estimate the maximum pressure that should be applied to the soil in order to avoid soil compaction, b) to evaluate the soil class and horizons susceptibility to compaction, c) to evaluate the soil management susceptibility to compaction, d) to evaluated the traffic effects on the soil structure, e) to assess the natural alleviation of the soil structure after a compaction event and f) to determine the natural soil mechanical resistance of the soil horizons that may impair the sustainable soil uses through time.

It is well known that soil organisms play an important role in various processes related with soil structure improvement (Jones et al., 1997; Stork & Eggleton, 1992;

Robert & Chenu, 1992; Spain & Lavelle, 2001). However, relationships among soil organisms density and diversity, as well as their management, on soil strength/structure, has not being found in literature as measured by precompression stress suggesting, therefore, a lack of information about the influence of the soil organisms in the soil bearing capacity.

Objective:

Present a methodology to obtain the Bearing Capacity Model.

Methodology Development

To obtain the Bearing Capacity Model, undisturbed soil samples with 0.064 m of diameter and 0.0254 m of height should be collected at a specific depth of interest using the Uhland soil sampler (Figures 1 and 2). The Collected undisturbed soil sample should have some soil in the top and in the bottom of the metal ring.

Figure 1: Uhland soil sampler and aluminum ring.

Figure 2: Undisturbed soil sample and the aluminum ring.

These undisturbed soil samples should be initially saturated in a tray with water up to 2/3 of the sample height for 24 hours and air dried in laboratory until a specific volumetric water content is obtained or submit the undisturbed soil sample to a specific water suction using tension plate assembly and pressure plate apparatus and then used in the uniaxial compression test according to steps 1 to 11 (Bowles, 1986; Wolff, 1993):

1. Cut off the portion of the soil sample remaining above the metal ring using a wire saw or knife. Place a glass plate over the ring and turn the undisturbed soil sample over. Cut off the soil extending beyond the bottom of the ring in the same manner as described for the surface portion. Place another glass plate on this surface, and again invert the undisturbed soil sample to an upright position,
2. Record all identifying information for the soil sample, such as project number, and other pertinent data, on the data sheet (Data sheet 1). Measure and record the height and the internal diameter of the ring before the sampling to facilitate the calculations relative to the volumetric water control in the laboratory. After the undisturbed soil sample is prepared, record the weight of the soil sample plus tare,

and from the soil trimmings obtain a representative sample for specific gravity determination.

3. Fit the bottom porous stone into the base of the consolidometer (Figure 3). Place a filter paper over the porous stone. Place the ring with the undisturbed soil sample therein on top of the porous stone.

Figure 3. Consolidometer unit.

4. Place a filter paper on top of the undisturbed soil sample, and then place the top porous stone and the loading plate in position.
5. Place the consolidometer containing the undisturbed soil sample in the loading device and attached the dial gage, and adjust it so that the stem of the dial indicator is centered with respect to the soil sample. Adjust the dial indicator to permit a maximum travel of the gage.
6. Adjust the loading device until it just makes contact with the undisturbed soil sample.
7. Read the dial indicator, and record the reading on the Data Sheet 1.
8. At a convenient starting time, apply the first pressure increment and simultaneously take deformation readings at elapsed times of 0.25. 0.5, 1, 2, 4, 8, 15, 30, 120 minutes, etc.
9. The pressure sequence used in the uniaxial compression tests is 25, 50, 100, 200, 400, 800 and 1.600 kPa. Each pressure should be applied until 90% of the maximum

deformation is reached (Taylor, 1948) and then the pressure should be increased to the next level. For the Brazilian soils 15 minutes has been enough to reach 90% of the maximum deformation in the partially saturated soils (Figure 4).

10. The 90% of maximum deformation is determined by plotting the dial readings on an arithmetic scale (ordinate) versus square root of the corresponding elapsed time (abscissa) and a straight line should be drawn through the data points in the initial part of the curve obtained until this line intercepts the y axis (dial readings). A second straight line is 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) (Figure 4).

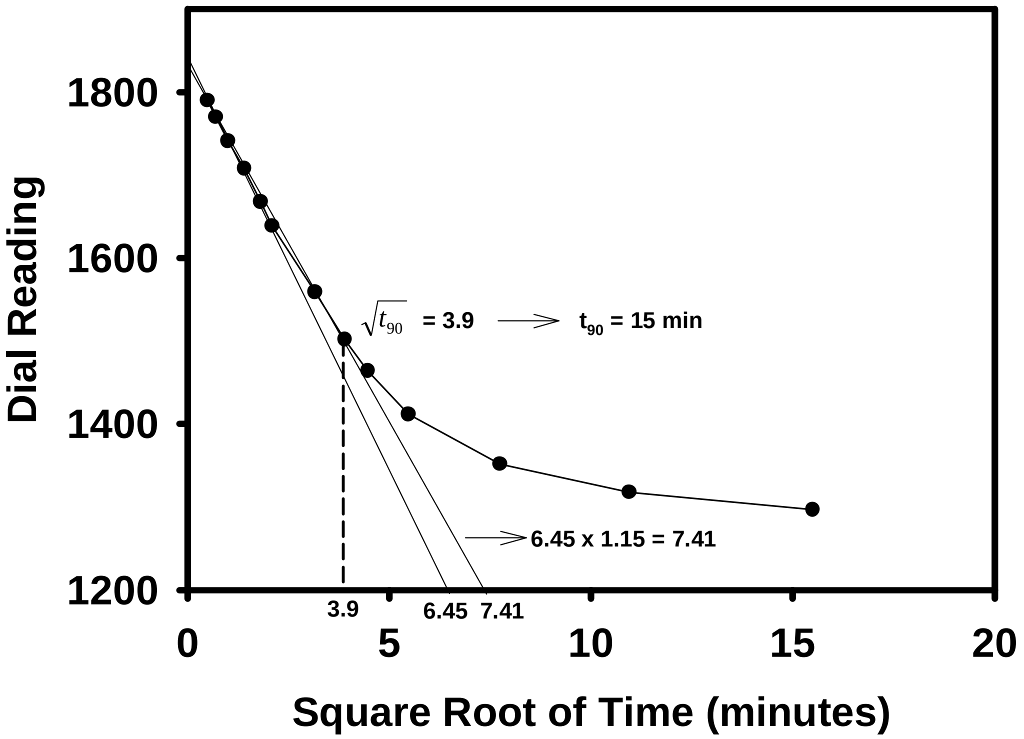


Figure 4. Curve of square root of time versus dial reading

11. When the applications of all pressures are finished, removed the applied pressure and the dial indicator and disassemble the apparatus and then oven dry the wet soil

sample to constant weight or during 24 hours at 105-110°C and weight and record in the Data Sheet 1 the dry weight of the soil sample plus tare.

To obtain the Bearing Capacity Model, the procedure below should be followed.

12. Plot the bulk density obtained for each applied pressure on a decimal scale (ordinate) and the corresponding applied pressure in a logarithmic scale (abscissa) obtaining the soil compression curve (Figure 5).

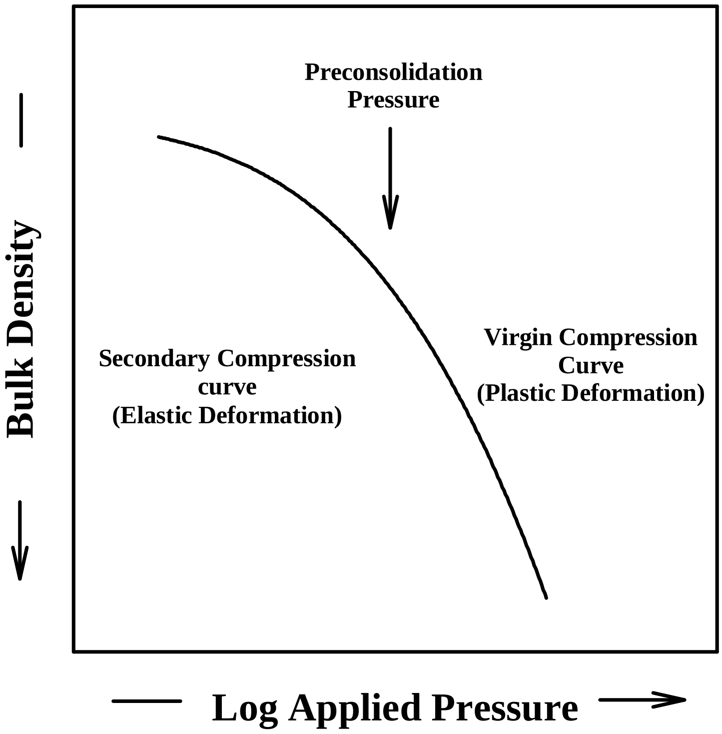


Figure 5. Soil compression curve. Source: Dias Junior (1994).

13. From the soil compression curves the precompression stress (σ_p) should be determined as a function of the volumetric water content (Θ) or as a function of the suction according to Dias Junior & Pierce (1995) (Table 1 and Figure 6) or using the Casagrande (1936) method (Figure 7) or another methods available in the literature.

Table 1. Spreadsheet for determination of the precompression stress (σ_p) from soil compression curves. Source: Dias Junior & Pierce (1995).

Stress	**Log Stress**	ρ_b	ρ_b **vcc**	ρ_b **reg**
25	1.3979	1.3905	1.2897	1.3845
50	1.6960	1.4444	1.3825	1.4502
100	2.0000	1.5097	1.5160	1.5160
200	2.3010	1.5878	1.5681	1.5847
400	2.6021	1.6712	1.6609	1.6474
800	2.9031	1.7537	1.7537	1.7131
1600	3.2041	1.8465	1.8465	
Method 1 (Suction <= 100 kPa)			**Method 3 (Suction > 100 kPa)**	
σ_p =	151 kPa		σ_p =	238 kPa
ρ_b =	1,53 Mg m^{-3}		ρ_b =	1,61 Mg m^{-3}

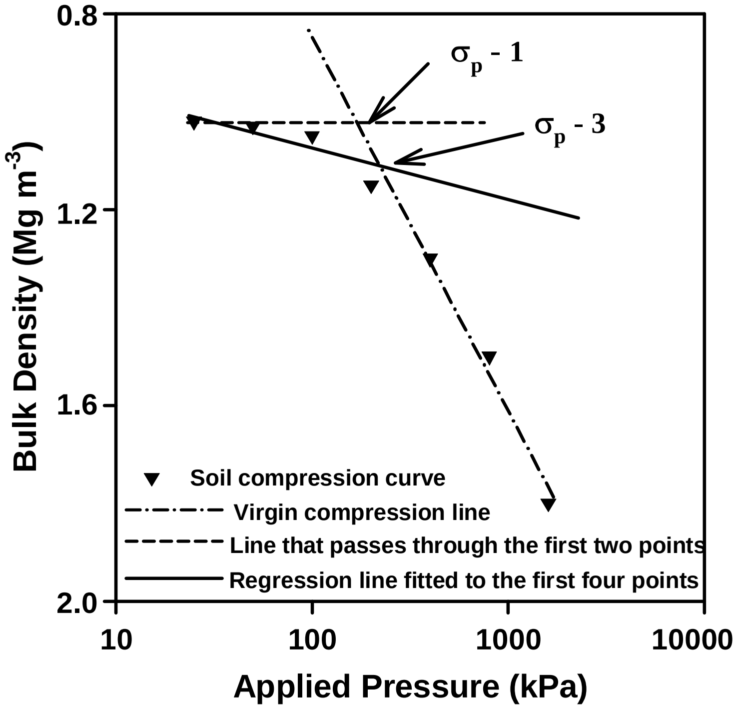


Figure 6. Computer screen of the soil compression curve showing the precompression stress (σ_p) obtained using method 1 and method 3. Source: Dias Junior (1994).

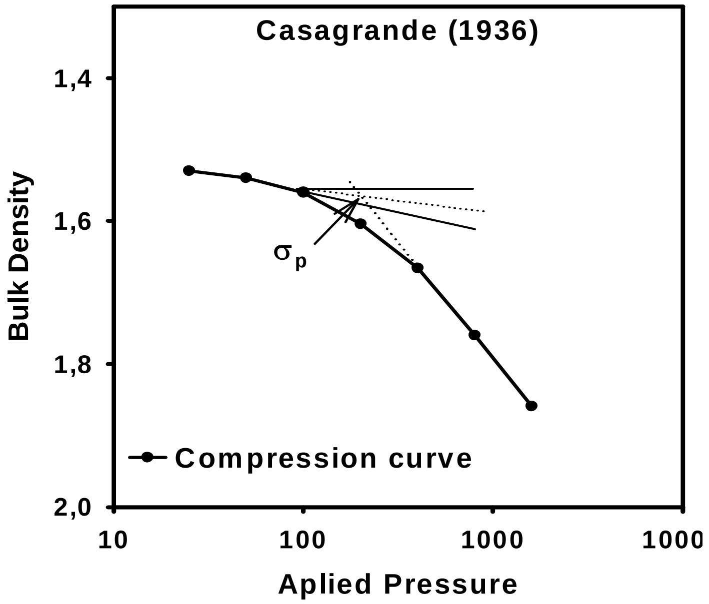
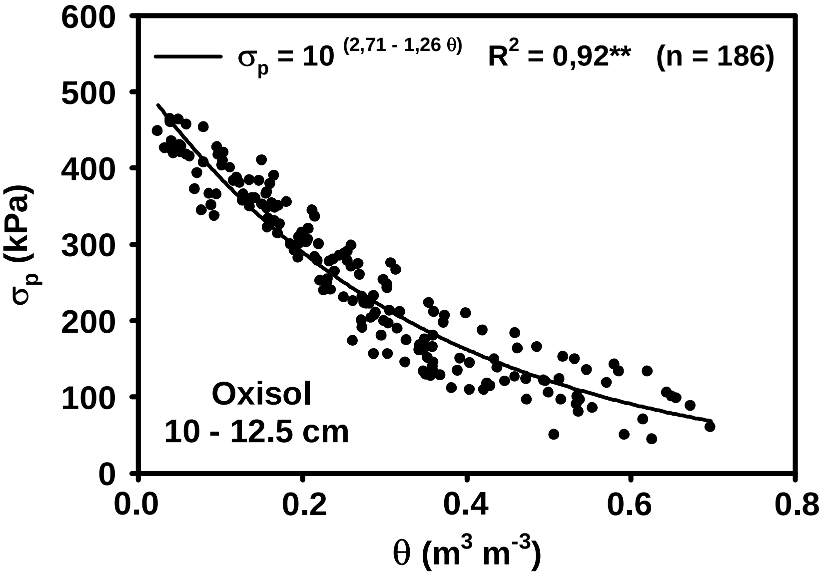


Figure 7. Casagrande (1936) method.

14. Then, a regression analyses should be accomplished using graphical software, to obtain the Bearing Capacity Model, which is the adjustment of precompression stress (σ_p) as a function of volumetric water content (ϴ) or suction (Figure 8).



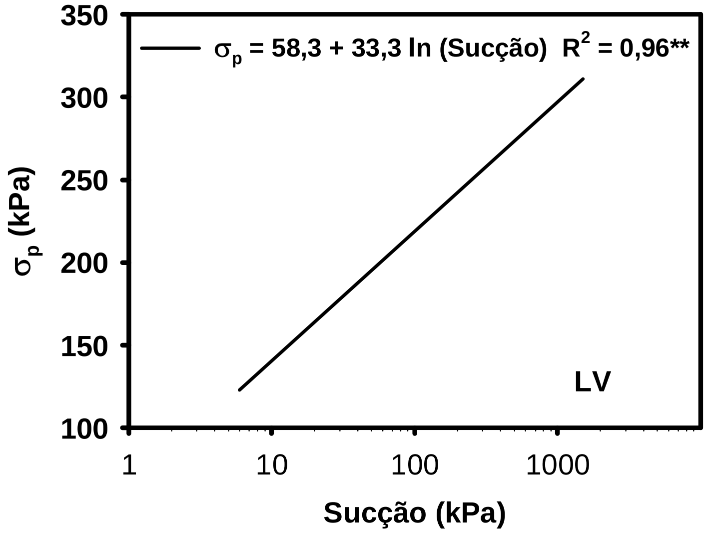


Figure 8. Bearing Capacity Model. Source: Dias Junior et al (2005) and Oliveira et al (2003)

15. Plot in the bearing capacity model the 95% confidence interval of the population (Figure 9).

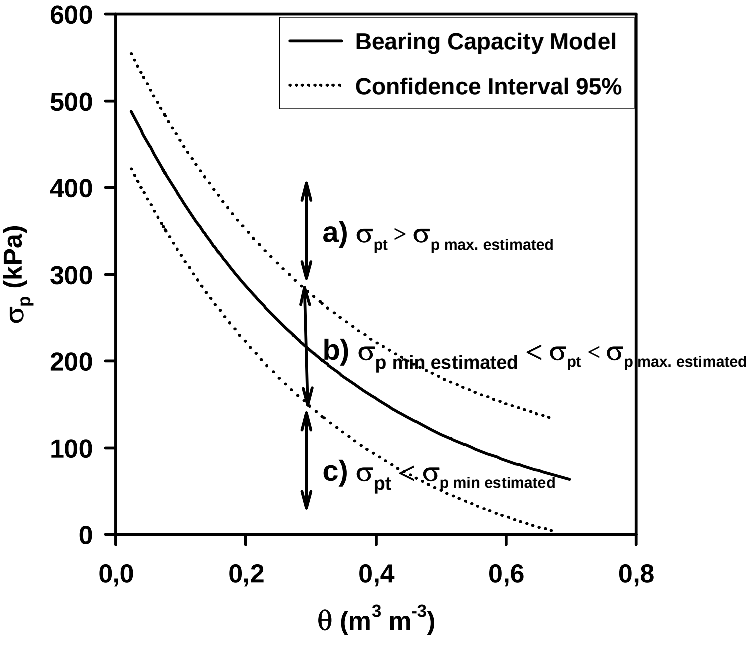


Figure 9 – Bearing Capacity Model and the criteria used to analyze the effect of the soil management on the precompression stress. Source: Dias Junior et al (2005)

16. Considering bearing capacities in agriculture, the application of pressures larger than the precompression stress should be avoided in order to avoid additional soil compaction, the Bearing Capacity Model (Figure 8), was then divided into three regions to evaluate the soil management effects on the soil structure according to Dias Junior et al (2005). The considered regions (Figure 9) are: a) the region where the precompression stress values determined after the soil management are larger than the higher limit of the confidence interval, being considered as the region where additional soil compaction happened; b) the region where precompression stress determined after the soil management are between the higher and lower limits of the confidence intervals. Although, the soil samples in this region did not suffer soil compaction, this region indicates the soil samples that might suffer soil compaction in the next operations if the applied pressures are larger than the higher limit of the confidence interval and c) a region where the precompression stress values determined after the soil management are smaller than the lower limit of the confidence interval.

17. To analyze the soil management effect on the precompression stress through time, a new set of undisturbed soil samples should be taken and submitted to the uniaxial compression test and the precompression stress should be determined as was described before. Then, the precompression stress should be plotted in the Bearing Capacity Model as a function of volumetric water content or suction at field condition (Figure 10).

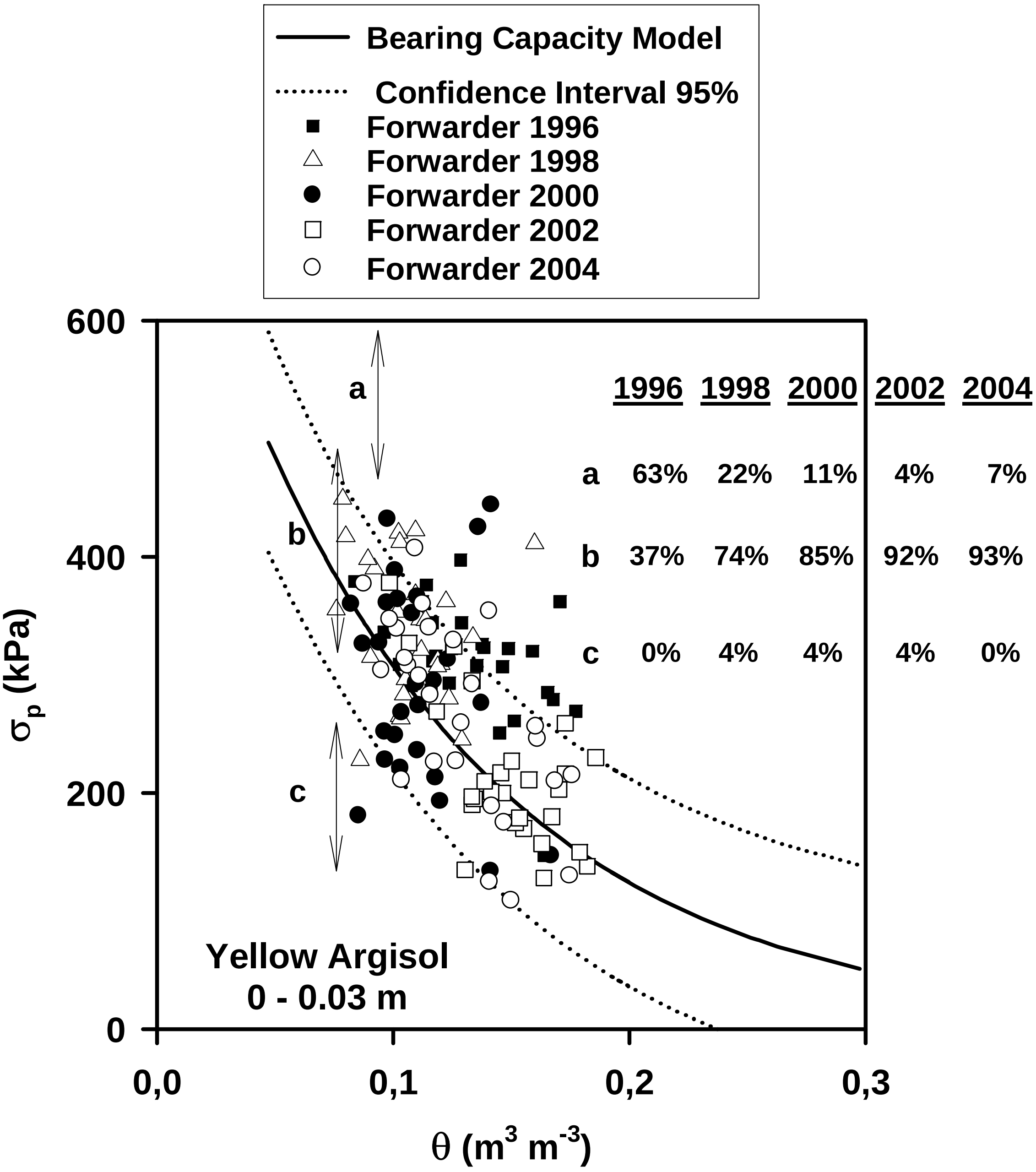


Figure 10. Bearing Capacity Model for a Yellow Argisol at 0-0.03 m depth. The symbols represent the values of the precompression stress determined in soil samples collected in 1996, 1998, 2000, 2002 and 2004, in the area where the Forwarder operations was done in 1996. (Source: Dias Junior, 2005).

COMPRESSIBILITY TEST – Data Sheet 1

DATE ______/______/______

Project: ________________________________

Company: ______________________________

Depth:_________________________________

Diameter of ring: ________________________

Initial height of ring: _____________________

Tare + M (wet soil) = _____________________

Tare + MS (dry soil)= _____________________

Tare = ________________________________

Particle Density = _____________ (g cm^{-3})

Sample number: ______________

ϴ (Volumetric water content) = _________ (kg kg^{-1})

Initial Bulk Density = ___________ (Mg m^{-3})

σ_p = ___________ (kPa)

$D_{s\sigma p}$ = ___________ (Mg m^{-3})

Pressure = 25 kPa

Clock Time	Elapsed time	Dial Reading
	0”	( )
	15”	( )
	30”	( )
	1’	( )
	2’	( )
	4’	( )
	8’	( )
	15’	( )

Pressure = 50 kPa

Clock Time	Elapsed time	Dial Reading
	0”	( )
	15”	( )
	30”	( )
	1’	( )
	2’	( )
	4’	( )
	8’	( )
	15’	( )

Pressure = 100 kPa

Clock Time	Elapsed time	Dial Reading
	0”	( )
	15”	( )
	30”	( )
	1’	( )
	2’	( )
	4’	( )
	8’	( )
	15’	( )

Pressure = 200 kPa

Clock Time	Elapsed time	Dial Reading
	0”	( )
	15”	( )
	30”	( )
	1’	( )
	2’	( )
	4’	( )
	8’	( )
	15’	( )

Pressure = 400 kPa

Clock Time	Elapsed time	Dial Reading
	0”	( )
	15”	( )
	30”	( )
	1’	( )
	2’	( )
	4’	( )
	8’	( )
	15’	( )

Pressure = 800 kPa

Clock Time	Elapsed time	Dial Reading
	0”	( )
	15”	( )
	30”	( )
	1’	( )
	2’	( )
	4’	( )
	8’	( )
	15’	( )

Pressure = 1600 kPa

Clock Time	Elapsed time	Dial Reading
	0”	( )
	15”	( )
	30”	( )
	1’	( )
	2’	( )
	4’	( )
	8’	( )
	15’	( )

EXEMPLE OF THE COMPUTATION DATA

Depth	**15**	**cm**	$\rho_{b\ i}$**=**	**1.48 kg dm^{-3}**
Ring Nº=	**16**		**Hs=**	**1.35 cm**
Rep	**1**		**Hi=**	**2.52 cm**
Ring+M=	**281.25**	**g**	∅ =	**6.41 cm**
Ring+Ms=	**269.66**	**g**	**Ui=**	**0.0962 kg kg^{-1}**
Ring=	**149.21**	**g**	**ei=**	**0.86**
Gs=	**2.76**		**ɵ=**	**0,1424 m^3 m^{-3}**

Pressure (kPa)	Reading (pol^{-4})	Reading (cm)	Delta H (cm)	Delta E	Void Index	Height (cm)	Volume dm^3	Ds Kg dm^{-3}
					0.8634	2.5200	0.0813	1.4812
25	351	0.0892	0.0892	0.0659	0.7975	2.4308	0.0784	1.5355
50	441	0.1120	0.0229	0.0169	0.7806	2.4080	0.0777	1.5501
100	590	0.1499	0.0378	0.0280	0.7526	2.3701	0.0765	1.5748
200	762	0.1935	0.0437	0.0323	0.7203	2.3265	0.0751	1.6044
400	1100	0.2794	0.0859	0.0635	0.6568	2.2406	0.0723	1.6659
800	1573	0.3995	0.1201	0.0888	0.5680	2.1205	0.0684	1.7602
1600	2019	0.5128	0.1133	0.0838	0.4842	2.0072	0.0648	1.8596

M = Weight of wet soil; Ms = Weight of dry soil; Gs = Specific gravity of solids; $\rho_{b\ i}$ = Initial bulk density; Hs = Height of solids; Hi = Initial height of the soil sample; ϕ = Diameter of the soil sample; Ui = Initial volumetric water content; ei = Initial void ratio; ɵ - volumetric water content.

Bulk density (kg dm^{-3})

$\rho_{b\,i} = \frac{Ms}{V}$, where v = volume of the undisturbed soil sample.

Example: $\rho_{b\,i} = \frac{269.66 - 149.21}{\pi \frac{(6,41)^2}{4} \times 2.52}$ = **1.48 kg dm^{-3}**

Height of solids (cm)

Hs = $\frac{Ms}{A \times Gs \times \gamma_w}$, where, A = area; γ_w = unit weight of water

Example: Hs = $\frac{269.66 - 149.21}{\pi \frac{(6,41)^2}{4} \times 2.76 \times 1}$ = **1.3524 cm**

Moisture Content (kg kg^{-1})

U = $\frac{Ma}{Ms}$, where Ma = weight of water.

Example: U = $\frac{281.25 - 269.66}{269.66 - 149.21}$ **= 0.0962 kg kg^{-1}**

Void Index

$e_i = \frac{Hi - Hs}{Hs}$

Example: $e_i = \frac{2.52 - 1.3524}{1.3524}$ **= 0.8634**

Reading (cm) = Reading (pol^{-4}) x 0.000254

Example: Reading (cm) = 351 x 0.000254 = **0.0892 cm**

Delta H (cm) = Reading $_{(i+1)}$ – Reading $_{(i)}$

Example: Delta H for 25 kPa = **0.0892 cm**

Delta H for 50 kPa = 0.1120 – 0.0892 = **0.0228 cm**

Delta e = $\frac{DeltaH}{Hs}$

Example: Delta e = $\frac{0.0892}{1.3524}$ = **0.0659**

Void Index = Void Index$_{(i)}$ – delta e$_{(i+1)}$

Example: Void Index for 25 kPa = 0.8634 – 0.0659 **= 0.7975**

Void Index for 50 kPa = 0.7975 – 0.0169 **= 0.7806**

Height (cm) = H$_{(i)}$ – Delta H $_{(i+1)}$

Example: Height for 25 kPa = 2.52 – 0.0892 **= 2.4308**

Height for 50 kPa = 2.4308 – 0.0229 **= 2.4079**

Volume (dm^{-3}) = Area$_{(i)}$ x H$_{(i)}$

Example: Volume initial = $\pi\frac{(6.41)^2}{4}\times 2.52\times 0.001$ **= 0,0813 dm^{-3}**

Volume for 25 kPa = $\pi\frac{(6.41)^2}{4}\times 2.4308\times 0.001$ **= 0,0784 dm^{-3}**

Volumetric Water Content (m^3 m^{-3})

$\theta = U \times \rho_{b\,i}$

Example: θ = 0.0962 x 1.4812 = **0.1425 m^3 m^{-3}**

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