DEVELOPMENT OF MATLAB ALGORITHM FOR THE CASAGRANDE MODEL FOR ANALYSIS OF PRE-CONSOLIDATION AND PRE-COMPRESSION STRESS IN SOILS

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ABSTRACT

Pre-consolidation/Pre-compression stress is a soil mechanical stability criterion, which is often used to determine the maximum external loads an undisturbed soil and structures can withstand without irreversible deformation. The most acceptable and widely use method of estimating pre-consolidation stress in the soil is the method developed by casagrande in 1936. In this method, determining pre-consolidation stress require accurate location of the point of maximum curvature on the soil compression curve which involves a lot of subjective perception or interpretation. In order to prevent such subjective interpretation in the determination of the point of maximum curvature, Mathematical model for determining the pre-consolidation stress was developed. The algorithm was implemented in MATLAB, thereby creating room to proper visualization of the graphical interface. The model was validated with data from Nigeria and Brazil. The results were compared with those generated with the previous EXCEL representation of the model by Dias Junior. The result showed a strong correlation with coefficient of determination $r^2 = 1$. The study contributes to a non-subjective way of estimating soil pre-consolidation/pre-compression stress from uni-axial experiment data, thereby assisting in prevention of soil compaction and consequent degradation.

KEYWORDS: Soil compaction, pre-consolidation stress, pre-compression stress, casagrande model, MATLAB

1. INTRODUCTION

The term ‘soil’ is used variedly depending on circumstances or profession. In soil science, soils are viewed as medium for plant growth, so the focus is on the organic rich part of the soil horizon (usually the topsoil), while the sediments below the weathered zone is referred to as the parent material. Moreover, soil scientists classify soils based on their physical, chemical, and biological properties which can be observed and measured. On the other hand, engineers use the soil as foundation to support structures and embankments and therefore define soil as any material that can be excavated with a shovel (no heavy equipment). They classify it based on the particle size, distribution, and the plasticity of the material. These classification criteria relate more to the behaviour of soils under the application of load, and this necessitate the need to determine the strength of the soil mass arising from its being subjected to varying degree of load.

In mechanised agriculture, the soil as a medium of cultivation is constantly subjected to loading in preparation for cultivation, during phyto-sanitary management and at harvest of cultivated crops. Thus the strength of the soil must be understood to ensure sustainable use.The strength of a soil determines its ability to support load; the factor which is strongly influenced by the amount of moisture present in the soil. Therefore, the intensive use of the soil without moisture control could lead to structural degradation in the soil (Pedrotti and Dias Junior, 1996). For example, soil compaction result when traffic of agricultural machines during a cropping season is not managed with reference moisture levels.

Soil compaction has been identified as one of the leading problem causing soil degradation (Barnes et al., 1971; Gupta et al., 1985; Larson et al., 1989 Canillas and Salokhe, 2002). Compaction restrict root penetration due to the insufficient root turgor pressure to overcome the mechanical resistance of the soil (Gysi, 2001), increases the bulk density and soil strength (Taylor, 1971; Lebert et al., 1989), decrease the total porosity and thereby limiting nutrient uptake, water infiltration and redistribution and, seedling emergence. The consequences of all these are decreased yields, increased erosion and power requirement for tillage.

In areas with intense rainfall, soil compaction had been recorded due to tillage and harvest operation carried out when the soil surface is wetter than optimal for wheel traffic (Silva et al., 1986, Dias Junior, 1997), in pasture, due to the excessive trampling of the cattle (Kondo and Dias Junior, 1999) and in forest areas due to the traffic during harvest operations and wood transport under inadequate soil water conditions (Dias Junior et al., 1999; Dias Junior, 2000).

However, soil compaction which is a major and about the most popular form of structural degradation can be avoided, if an early detection and monitoring process is established (Dias Junior, 1994; Dias Junior and Pierce, 1995; Ajayi et al., 2013). Among several methods that have been proposed, the use of soil compression curve has stand the test of time. The soil compression curve delineates the behaviour of soil into zones of Elastic deformation (secondary compression curve) and the zones of plastic deformation (virgin compression curve). The pre-consolidation/pre-compression pressure is widely agreed as the point that separates the two on a compression curve (Dias Junior and Pierce, 1995; Horn et al., 1995). In defining the pre-consolidation pressure point on a soil compression curve, it is necessary to establish the optimum point of curvature on the curve. Determining this has been a subject of intense interest in soil mechanics and soil physics study, resulting in the development of graphical mean of estimation. However, the graphical determination is been burdened by a lot of subjectivity, thus Casagrande 1936, develop a method of determining pre-compression pressure from the soil compression curve.

The pre-consolidation pressure/ pre-compression stress (σ_p) is an indication of soil strength or maximum previously applied stress sustained by a soil. It defines the limit of elastic deformation in the soil compression curves (Holtz and Kovacs, 1981, Dias Junior and Pierce, 1995; Defossez and Richard, 2002), and may be used as a quantitative indicator of soil structure sustainability. Thus, in agriculture, application of stress greater than the pre-compression stress should be avoided. The change in pre-compression stress σ_p as a function of moisture content is important for root growth and also essential for determining the load support capacity of the soil.

Considering its importance to soil management, the determination of pre-consolidation pressure should be made less subjective, therefore the elimination of this in the location of the point of maximum curvature necessitate the development of a computer model to accurately determine the pre-consolidation pressure emanating from the casagrande model on the soil compression curve.

Therefore, the study is aimed at: (a) developing an algorithm that solves the Casagrande equation, (b) develop a graphical interface for the visualisation and interpretation of Casagrande model solution and apply the developed model to dataset of stress versus strain from four different soil samples collected from Brazil and Nigeria, comparing the result with those estimated from Excel spreadsheet representation of the model.

2. METHODOLOGY

2.1 Modelling Process for Pre-compression Determination

The principles of mathematical modelling and computer simulation is based on the idea that if the goal of the particular problem can be quantified, it may be possible to express it mathematically so that it may be possible to device a computational skill or method that will yield a solution to the problem. Modelling process used in this project is broken into 5 steps as outlined below:

2.1.1 Problem Definition

In order to build a model of a system to represent something else, or develop a model through a mathematical expression, it is necessary to first list out the factors to be considered and identify the goal to be achieved. In many cases the physical situation must be analysed and how some variable parameters affect or influence the model to be developed must be recognised and applied to the simplified form.

In this study, the major concern is to eliminate the subjective interpretation of the turning point or point of maximum curvature on the soil compression curve to accurately determine the soil pre-compression stress. The turning point is estimated from the casagrande model, which this work intends to represent in well-defined and structured algorithm.

2.1.2 Data Collection/Analysis

The dataset used for the implementation of the model were obtained from uniaxial compression test experiment on soils samples collected at the B-Horizon in locations in Brazil (Lavras, Uberladia and Rio Gran de Sul) and a location in Nigeria (Ire Ekiti). The dataset of the samples collected are shown in Tables 1 – 4:

Table 1: First Data Used for Validating the Model (Lavras)

Pressure (kPa)	Reading (pol^{-4})	Reading (cm)	Delta H (cm)	Delta E	Void Index	Height (cm)	Volume dm^3	ρ_b kg dm^{-3}
					1.3550	2.5100	0.0797	1.1253
25	70	0.0178	0.0178	0.0167	1.3383	2.4922	0.0792	1.1333
50	282	0.0716	0.0538	0.0505	1.2878	2.4384	0.0775	1.1583
100	647	0.1643	0.0927	0.0870	1.2008	2.3457	0.0745	1.2041
200	1112	0.2824	0.1181	0.1108	1.0900	2.2276	0.0708	1.2680
400	1612	0.4094	0.1270	0.1192	0.9708	2.1006	0.0667	1.3446
800	2095	0.5321	0.1227	0.1151	0.8557	1.9779	0.0628	1.4280
1600	2495	0.6337	0.1016	0.0953	0.7604	1.8763	0.0596	1.5054

Table 2: Second Data Used for Validating the model (Uberladia)

Pressure (kPa)	Reading (pol^{-4})	Reading (cm)	DeltaH (cm)	DeltaE	Void Index	Height (cm)	Volume dm^3	ρ_b kg dm^{-3}
					1.3259	2.5000	0.0794	1.1393
25	102	0.0259	0.0259	0.0241	1.3018	2.4741	0.0786	1.1513
50	179	0.0455	0.0196	0.0182	1.2836	2.4545	0.0780	1.1605
100	270	0.0686	0.0231	0.0215	1.2621	2.4314	0.0772	1.1715
200	370	0.0940	0.0254	0.0236	1.2385	2.4060	0.0764	1.1839
400	546	0.1387	0.0447	0.0416	1.1969	2.3613	0.0750	1.2063
800	887	0.2253	0.0866	0.0806	1.1163	2.2747	0.0723	1.2522
1600	1289	0.3274	0.1021	0.0950	1.0213	2.1726	0.0690	1.3110

Table 3: Third Data Used for Validating the model (Rio Gran de Sul)

Pressure (kPa)	Reading (pol^{-4})	Reading (cm)	DeltaH (cm)	DeltaE	Void Index	Height (cm)	Volume dm^3	ρ_b kg dm^{-3}
					1.4687	2.5500	0.0810	1.0734
25	20	0.0051	0.0051	0.0049	1.4638	2.5449	0.0808	1.0756
50	58	0.0147	0.0097	0.0093	1.4545	2.5353	0.0805	1.0797
100	166	0.0422	0.0274	0.0266	1.4279	2.5078	0.0797	1.0915
200	355	0.0902	0.0480	0.0465	1.3814	2.4598	0.0781	1.1128
400	611	0.1552	0.0650	0.0630	1.3185	2.3948	0.0761	1.1430
800	947	0.2405	0.0853	0.0826	1.2358	2.3095	0.0734	1.1852
1600	1420	0.3607	0.1201	0.1163	1.1195	2.1893	0.0696	1.2503

Table: 4 Fourth Data Used for Validating the model (Ire)

Pressure (kPa)	Reading (pol^{-4})	Reading (cm)	DeltaH (cm)	Delta E	Void Index	Height (cm)	Volume dm^3	ρ_b kg dm^{-3}
					1.3728	2.5200	0.0801	1.1168
25	5	0.0013	0.0013	0.0012	1.3716	2.5187	0.0800	1.1174
50	20	0.0051	0.0038	0.0036	1.3680	2.5149	0.0799	1.1191
100	74	0.0188	0.0137	0.0129	1.3551	2.5012	0.0795	1.1252
200	195	0.0495	0.0307	0.0289	1.3262	2.4705	0.0785	1.1392
400	415	0.1054	0.0559	0.0526	1.2736	2.4146	0.0767	1.1656
800	762	0.1935	0.0881	0.0830	1.1906	2.3265	0.0739	1.2097
1600	1248	0.3170	0.1234	0.1162	1.0743	2.2030	0.0700	1.2775

2.1.3 Model Formulation

At this stage of the model development, each factor (stress and bulk density) is given a sense of value by assigning a variable. The main objective of model formulation is to eliminate error of locating the point of maximum curvature or to make it as small as possible and then develop a computer model to represent the model formulation.

In order to eliminate this error, computational skill was adopted to develop a MATLAB algorithm for the casagrande model. The parameters used in developing the computer model are; stress and bulk density. The stress and bulk density therefore generate the finite divided difference of the curve (FD), second derivative (SD), Virgin Compression Line (VL) and the regression lines (RL).

(i) Virgin Compression Model

The model is used to estimate the deformations that could occur when pressure greater than the pre-compression stress is applied to the soil. This model takes the general form illustrated in equation (3). It is necessary to first calculate the finite difference (FD) and second derivative (SD).

The equation of the finite difference (FD) and second derivative (SD) (with x_i corresponding to the logarithm of the applied stress interval and y_i corresponding to void ratio or dry bulk density intervals) are as illustrated below:

$$FD_j = \frac{y_{i+1} - y_i}{x_{i+1} - x_i} \quad \text{---} \quad (1)$$

$$SD_j = FD_{j+1} - FD_j \quad \text{--} \quad (2)$$

j = 0, 1, 2, 3, 4, ----,
i = 0, 1, 2, 3, 4, ----,

where,
FD = Finite divided difference of the curve; SD = Second derivative; i = Number of stress and bulk density values used; j = Number of times to iterate

The Virgin Compression Line (VCL) representing the plastic region on the soil compression curve can be found from the formula below:

$$VCL = \frac{y_{final} - y_{final-1}}{x_{final} - x_{final-1}}\left(x_{i+1} - x_{final-1}\right) + y_{final-1} \quad \text{---------------------------------} \quad (3)$$

(ii) Regression/Recompression Model
This model describes the region in which the soil will undergo a recoverable deformation. The model takes the general form illustrated in equation (4) and (5) below:

$$\rho_b reg(1) = \frac{y_{i+1} - y_i}{x_{i+1} - x_i}\left(x_{i+1} - x_i\right) + y_i \quad \text{----------------------------------} \quad (4)$$

$$\rho_b reg(2) = c + x_{i+1}(slope) \quad \text{---} \quad (5)$$

where,
x_1 and y_1 = The data pair where second derivative (SD) value is minimum
$\rho_b reg(1)$ = The first regression line that passes through the first two data point.
$\rho_b reg(2)$ = Regression line fitted to the first four data points
C = The intercept of the linear regression line for the first four data point on y-axis
Slope = The gradient of the linear regression line for the first four data point of bulk density (y_1, y_2, y_3, y_4) and Log of stress (x_1, x_2, x_3, x_4), taken the form $y = a + bx$ (linear model).

The point of interception between $\rho_b reg(1)$, $\rho_b reg(2)$ and virgin compression line correspond the soil pre-compression stress.

(iii) Soil Management Model
The soil management model refers to the soil pre-compression stress model that may be used to estimate the maximum pressure that can be applied to the soil in order to avoid structure degradation. The model takes general form illustrated in equation (7) and (10) including its corresponding bulk density model in equation (8) and (11).

$$Log(\sigma_p 1) = \frac{FD_{\min}(-x_2)) + y_2 - y_{final} - FD_{\max}(-y_{final}))}{FD_{\max} - FD_{\min}} \quad (6)$$

$$\sigma_P 1 = Anti\log(Log\sigma_p 1) \quad (7)$$

$$\rho_{b1} = FD_{\min}((\sigma_p 1 - (x_2)) + y_2 \quad (8)$$

$$Log(\sigma_p 2) = \frac{c + ((FD_{\max})(x_{final})) - y_{final}}{FD_{\max} - slope} \quad (9)$$

$$\sigma_P 2 = Anti\log((Log(\sigma_p 1)) \quad (10)$$

$$\rho_{b2} = c + slope(\log(\sigma_p 2)) \quad (11)$$

where,

σ_{p1} = Pre-compression stress when suction (i.e the removal of water and air from the soil by the application of load) is less than 100kpa

σ_{p2} = Pre-compression stress when suction is greater than 100kpa. Parameters such as intercept (c), slope, FD_{min}, FD_{max}, are the same as described in equation (1), (2) and (5).

2.1.4 Model Solution/Analysis

A solution of the model was attempted using the appropriate computational skill or method. The solution to the problem was designed from Graphical User Interface Development Environment (GUIDE) with the programme of the model written and implemented in M-file of MATLAB.

2.2 The MATLAB

MATLAB® is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include:

i) Mathematics and computation
ii) Algorithm development
iii) Modeling, simulation, and prototyping
iv) Data analysis, exploration, and visualization
v) Scientific and engineering graphics
vi) Application development, including graphical user interface building MATLAB in an interactive system whose basic data element is an array that does not require dimensioning. This allows the MATLAB to solve many technical computing problems, especially iterating values.

It should therefore be noted that in this paper work a lot of values were iterated which actuate the need of using MATLAB software. The programme and the codes generated were saved and run in an M-file

2.3 M-file

To take advantage of MATLAB's full capabilities in this project, a long sequence of statement was constructed. This was done by writing the commands in a file and calling it from within MATLAB. Such files are called "m-files" because they must have the file name extension ".m". This extension is required in order for these files to be interpreted by MATLAB.

2.4 The Program Designing

The stress and the bulk density data (with the mass of solid, diameter of ring used in determining the bulk density during experiment considered) were input into the computer programme by importing an EXCEL spreadsheet to generate the finite divided difference, Second derivative, virgin compression line (VCL) and the regression values. This is only possible whenever the stress and bulk density are selected, this can be applicable to many data as possible. The results of the iterated values that produces the casagrande graphical interface were arranged in an array in the Graphical User Interphase (GUI) of the MATLAB including the output values of the pre-compression/pre-consolidation stress. The algorithm and flow chart designed for the programme following the step by step of eliminating the subjective interpretation of the point of maximum curvature is as described in Figure 1.

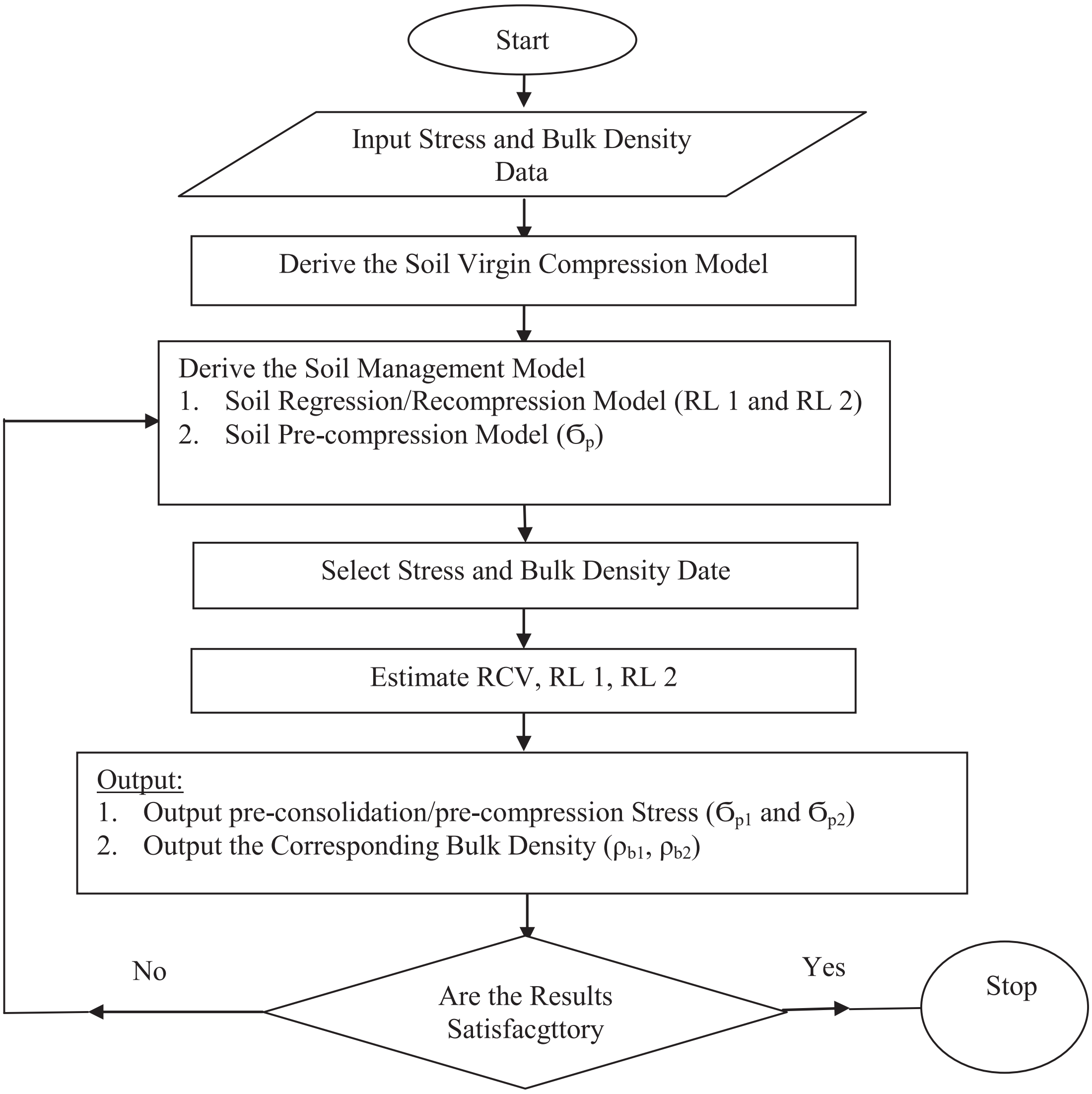

Figure 1: The Program Flow Chart for the Casagrande Model

3. RESULTS AND DISCUSSION

After the program for the model had been test run, it was validated with sample collected from Nigeria (Oye Ekiti) and Brazil (Lavras, Uberladia and Rio Gron resul,) at the B-Horizon .The model was tested before usage by using data from the uni-axial comprexibility test. The results were compared with a previous EXCEL representation of the model by Dias Junior, 1994. The results with its corresponding graphical representation for the Lavras sample collected at the B-Horizon is as illustrated in Table 5 – 8 and the graphical interface is as shown in Figure 2 – 5.

Table 5: Computer model result for the Lavras Set of Data for Validating the model

Stress	Log(Stress)	Bulk Density	RCV	RL(1)	RL(2)
25	1.3979	1.1333	1.0410	1.1333	1.1234
50	1.6990	1.1583	1.1184	1.1583	1.1684
100	2.0000	1.2041	1.1958	1.1833	1.2134
200	2.3010	1.2680	1.2732	1.2083	1.2584
400	2.6021	1.3446	1.3506	1.2333	1.3034
800	2.9031	1.4280	1.4280	1.2583	1.3484
1600	3.2041	1.5054	1.5054	1.2833	1.3934

σ_{p1} = 84.7597 $x_1 = 1.92819$

σ_{p2} = 145.7670 $x_2 = 2.16366$

Bulk density (1) = 1.17734 Bulk density (2) = 1.23788

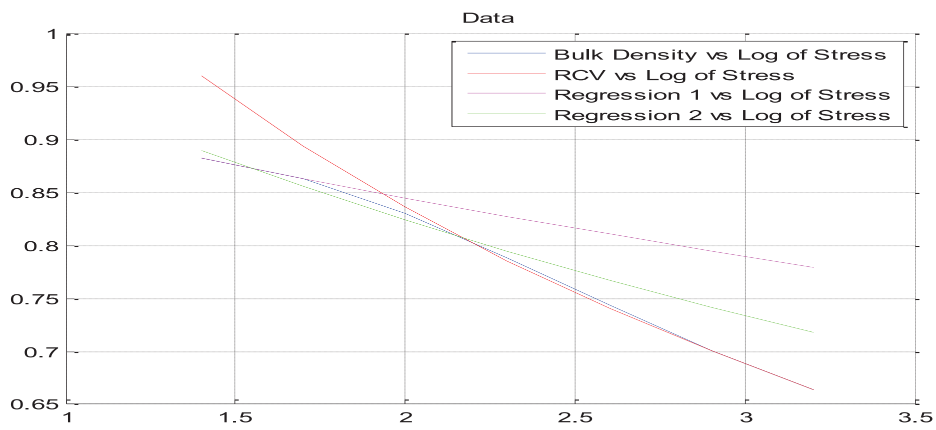

Figure 2: Graphical Interface for Estimating Pre-compression Stress for the Lavras Set of Data

Table 6: Computer model result for the Uberladia Set of Data for Validating the model

Stress	Log(Stress)	Bulk Density	RCV	RL(1)	RL(2)
25	1.3979	1.1513	0.9579	1.1513	1.1505
50	1.6990	1.1605	1.0168	1.1605	1.1613
100	2.0000	1.1715	1.0756	1.1696	1.1722
200	2.3010	1.1839	1.1345	1.1788	1.1831
400	2.6021	1.2063	1.1933	1.1880	1.1940
800	2.9031	1.2522	1.2522	1.1972	1.2048
1600	3.2041	1.3110	1.3110	1.2063	1.2157

$\sigma_{p1} = 371.12$ $x_1 = 2.56951$

$\sigma_{p2} = 403.541$ $x_2 = 2.60589$

Bulk density (1) = 1.18698 Bulk density (2) = 1.19409

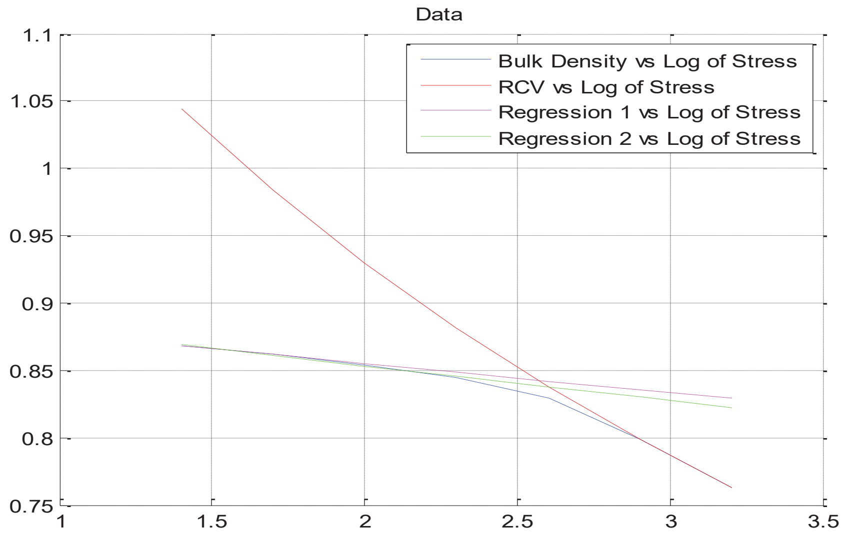

Figure 3: Graphical Interface for Estimating Pre-compression Stress for the Uberladia Set of Data

Table 7: Computer model result for the Rio Gron Resul Set of data for validating the Model

Stress	Log(Stress)	Bulk density	RCV	RL(1)	RL(2)
25	1.3979	1.0756	0.8708	1.0756	1.0714
50	1.6990	1.0797	0.9386	1.0797	1.0837
100	2.0000	1.0915	1.0064	1.0838	1.0961
200	2.3010	1.1128	1.0742	1.0879	1.1084
400	2.6021	1.1430	1.1419	1.0920	1.1207
800	2.9031	1.1852	1.2097	1.0961	1.1331
1600	3.2041	1.2503	1.2775	1.1002	1.1454

Ϭp1 = 290.125 x_1 = 2.46258

Ϭp2 = 402.857 x_2 = 2.60515

Bulk density (1) = 1.09006 Bulk density (2) = 1.12086

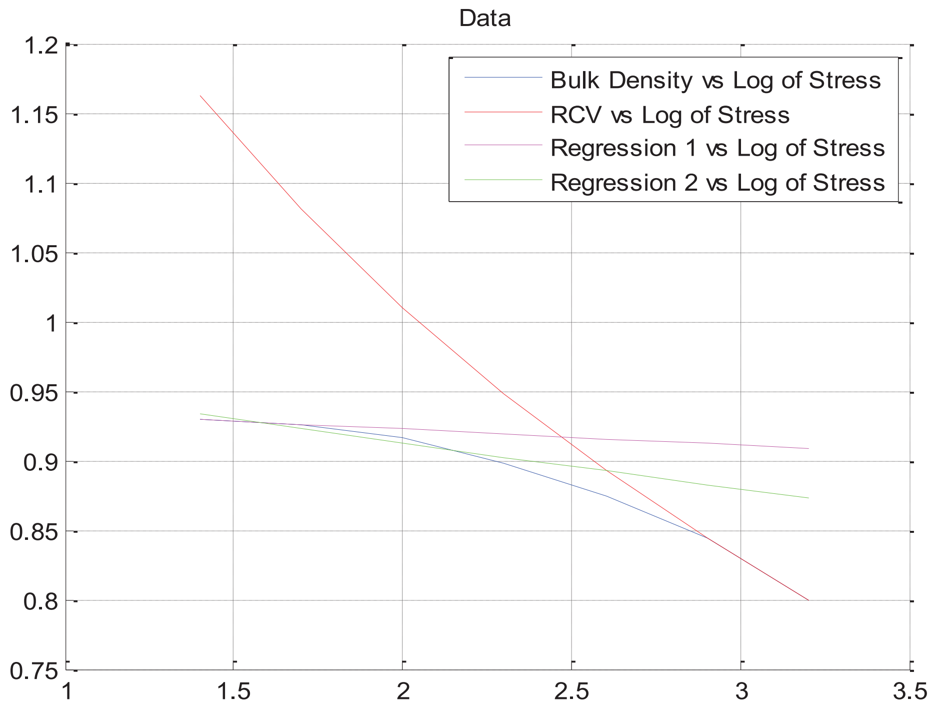

Figure 4: Graphical Interface for Estimating Pre-compression Stress for Rio Gron Resul Set of Data

Table 8: Computer Model Result for the Ire Set of Data for Validating the Model

Stress	Log(Stress)	Bulk density	RCV	RL(1)	RL(2)
25	1.3979	1.1174	0.8708	1.1174	1.1145
50	1.6990	1.1191	0.9386	1.1191	1.1216
100	2.0000	1.1252	1.0064	1.1208	1.1288
200	2.3010	1.1392	1.0742	1.1225	1.1360
400	2.6021	1.1656	1.1419	1.1242	1.1431
800	2.9031	1.2097	1.2097	1.1258	1.1503
1600	3.2041	1.2775	1.2775	1.1275	1.1575

Ϭp1 = 331.912 x_1 = 2.52102

Ϭp2 = 405.428 x_2 = 2.60791

Bulk density (1) = 1.12369 Bulk density (2) = 1.1426

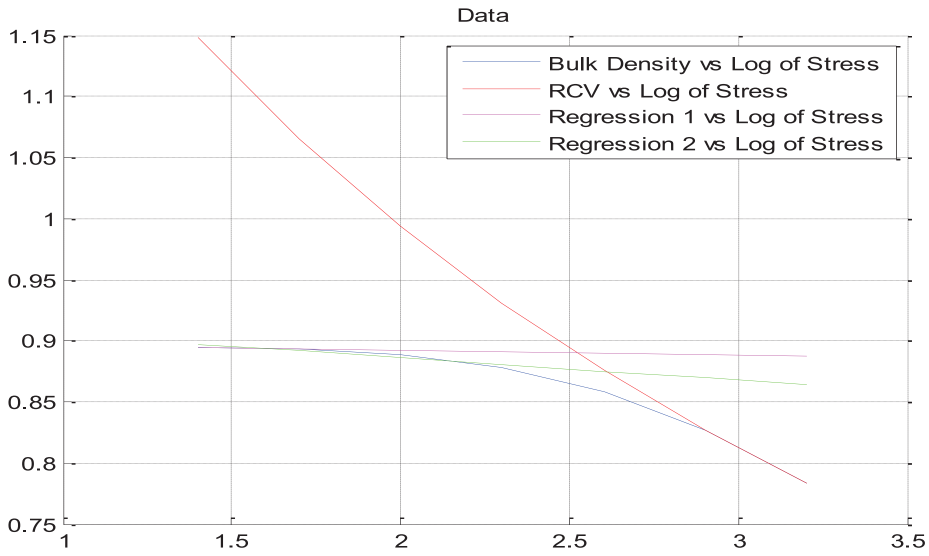

Figure 5: Graphical Interface for Estimating Pre-compression Stress for the Ire set of data

The model implemented using the MATLAB software produced the results in Table and Figure 2 - 5 by using some available data from uni-axial compressibility test collected in Nigeria (Ire) and Brazil (Lavras, Uberladia and Rio Gron resul) at the B-Horizon. The graphical interface for the visualisation and interpretation of the casagrande model for the data collected are as described in Figure 2 - 5. The figures show stress versus bulk density in which the stress/loads applied to the soil are at the interval of 25, 50, 100, 200, 400, and 800. Figure 2 - 5 describe the graphical representation of the casagrande model, consisting of the soil Virgin Compression Line (VCL) or Re-compression virgin (RCV) that describe the region of plastic or permanent deformation and the regression lines (RL1 and RL2) representing the zone or region of recoverable/elastic deformation. The point of interception of RCV and RL1 correspond to the pre-consolidation stress (P_1) while the point of interception of RCV and RL2 correspond the soil pre-consolidation stress (P_2) as shown in figure 3.1-3.4. The soil pre-consolidation stress separates the two zones on soil compression curve.

Table 9 and Figure 6 - 7 below show that pre-consolidation stress output from MATLAB strongly correlate with the previous Excel representation of the model by Dias Junior 1994. This implies that the prediction from the MATLAB was accurate.

Table 9: Comparison of Pre-consolidation Stress (P_1 and P_2) Estimated from MATLAB and EXCEL Representation of the Model

S/N	EXCEL RESULT		MATLAB OUTPUT	
	P_1(kpa)	P_2(kpa)	P_1(kpa)	P_2(kpa)
1	84.5294	145.0957	84.7597	145.7670
2	371.1197	403.5412	371.12	403.541
3	290.1248	402.8570	290.125	402.857
4	331.9118	405.4283	331.912	405.428

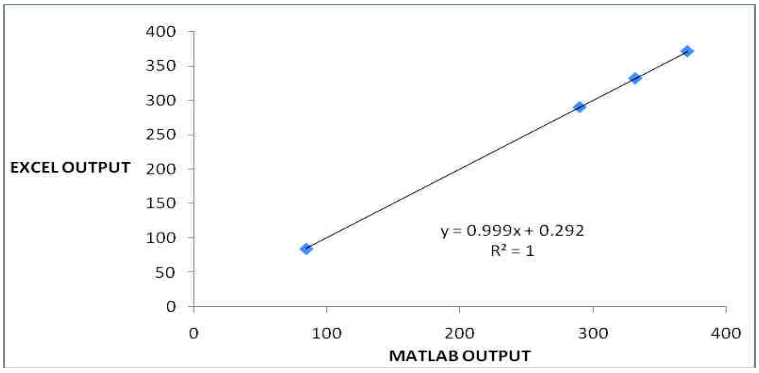

Figure 6: The Relationship of Pre-compression Stress (P_1) Result Estimated from Excel and the Output from MATLAB

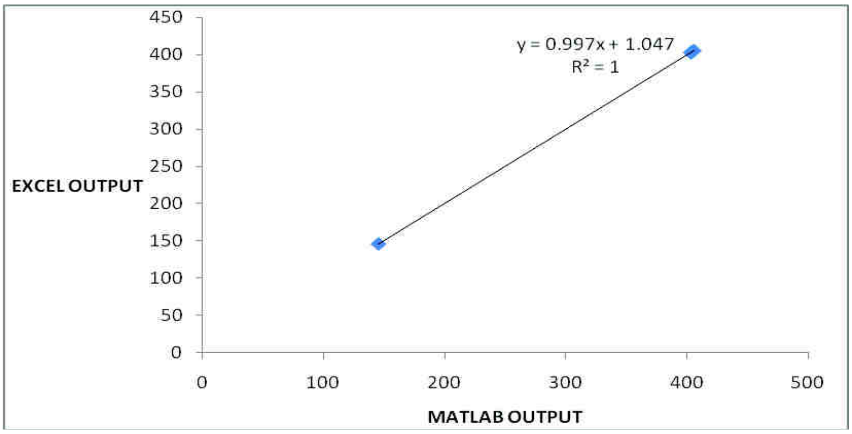

Figure 7: The Relationship of Pre-compression Stress (P_2) Result Estimated from Excel and the Output from MATLAB

4. CONCLUSION

This study presents a MATLAB algorithm for determining the soil pre-consolidation stress by eliminating the subjective interpretation of the point of maximum curvature on the soil compression curve, the model was validated with seven inputs of soil bulk density and stress i.e the applied load).

The model evaluation was carried out by comparing the computer model result with the previous EXCEL representation of the model by Dias Junior 1994, the comparison of MATLAB output with the EXCEL representation of the Model shows a strong degree of correlation of r^2=1, therefore showing that the MATLAB output is accurate. Based on the MATLAB algorithm developed for the Casagrande model using the MATLAB software, it can be concluded that the subjective interpretation of the point of maximum curvature or minimum radius of curvature was eliminated. In addition the soil pre-compression stress was accurately determined. This fact was established based on the fact that the predicted results of the model match/agree with EXCEL representation of the model.

REFERENCES

Alawaji H.A, 2001. Shear induced collapse settlement of arid soils

Assalay.A.M, Jefferson.I, Ragers.C.D.F, Smalley.I.J, 1997. Fragipan formation in loess soils: development of the Bryant hydroconsolidation hypothesis.

Assouline. S, 2002. Modelling soil compaction under uniaxial compression.

Badawy S I.F, Hussain M.A, 2004. Effect of starting material particle size on its agglomeration iour in high shear wet granulation

Canillas, E. C. and Salokhe, V. M., 2002. A decision support system for compaction assessment in agricultural soils. Soil Till. Res. 65, 221-230.

Constantini E.A.C, Damiani. D, 2004. Clay minerals and the development of quarternary soils in central italy.

Dias Junior, M. S., 1994. Compression of three soils under long-term tillage and wheel traffic. Ph.D Thesis, Michigan State University.

Dias Junior, M. S., 2000. Compactação do solo. In R.F. Novais; V.H. Alvarez V and C.E.G.R. Schaefer (Editors). Topics in Soil Science. Soc. Bras. Ci. Solo. pp. 55-94.

Dias Junior, M. S., 2002a. Compactação do solo. Relatório de Pesquisa. Aracruz Celulose S.A. 72pp.

Dias Junior, M. S., 2002b. Avaliação de impactos de sistemas de colheita nas características físicas dos solos. Relatório de Pesquisa. Celulose Nipo- Brasileira S.A.113 pp.

Dias Junior, M.S. 2000. Compactação do solo. Relatório Técnico. 46p.

Dias Junior, M.S., Ferreira, M.M., Fonseca, S., Silva, A.R., Ferreira, D.F., 1999.

Avaliação quantitativa da sustentabilidade estrutural dos solos em sistemas florestais na região de Aracruz – ES. R. Árv., 23, 371-380.

Dias Junior, M. S. and Miranda, E.E.V., 2000. Comportamento da curva de compactação de cinco solos da região de Lavras (MG). Ci. Agrot. 24, 337- 346.

Dias Junior, M. S. and Pierce, F.J., 1995. A simple procedure for estimating preconsolidation pressure from soil compression curves. Soil Tech., 8, 139 Dijkstra T.A, Smalley I.J, Rogers C.D.F, 1995. Particle packing in loess deposits and the problem of structure collapse and hydroconsolidation

Donkor, N.T.; Gedir, J.V.; Hudson, R.J.; Bork, E.W.; Chanasky, D.S. and Naeth, M.A. (2001): Impact of grazing systems on soil compaction and pasture production in Alberta. Canadian J. of Soil Science, 2001

Greenwood, K.L. and Mc Kenzie, B.M. (2001): Grazing effects on soil physical properties and the consequences for pastures: a review. Austr. J. of experimental Agriculture, 2001, 41 1231-1250

Gupta, S.C.; Hadas, A.; Voorhees, W.B.; Wolf, D.; Larson, W.E. and Schneider,E.C., 1985. Development of quids for estimating the ease of compaction of world soils. Bet Dagan, Israel. Research Report, Binational Agric. Res. Development, University of Minnesota, 178 pp.

Gysi, M., 2001. Compaction of a Eutric Cambisol under heavy wheel traffic in Switzerland: Field data and a critical state soil mechanics model approach. Soil Till. Res. 61, 133-142.

Hartge, K. H., R. Horn 1991. Einführung in die Bodenphysik. Stuttgart, Ferdinand Enke Verlag. 303 S.

Horn, R. 2001. Die verformung von Böden – Ursachen und Folgen für eine nachhaltige

Horn R., Domzal H., Slowinska-Jurkiewicz A., C. Van Ouwerkerk 1995. Soil compaction processes and their effects on the structure of arable soils and the environment, Soil & Tillage Research 35 (1995): 23-36Kanton Zürich (1995). Kantonaler Richtplan. Kantonsratsbeschluss

Lesturgez Gregory, Daniel Tessier, Elliane Huard, Hartmann.C, and Poss.R, 2004. Collapsing and traffic load: the formation of dense layer in a sandy soil.

Miller H, Djerbib Y, Jefferson I.F and Smalley I.J, 1998. Modelling the Collapse of Metastable Loess Soils

Semmel H., R. Horn 1994. Spannungen und Spannungsverteilungen in Ackerböden aufgrund von Befahrungen - Überlegungen zur Druckfortpflanzung und der mechanischen

Belastbarkeit von Böden. Landbauforschung Völkenrode *147*, Mitt. d. Bundesforsch. anst. f. Landwirtsch. Braunschweig-Völkenrode (FAL):41-76

Zhang, H.Q. and Horn, R. 1996: Einfluss der Beweidung auf die physikalischen Eigenschaften einer Salzmarsch im Deichvorland (I): diegesättigte Wasserleitfähigkeit und das Bodengefüge. Z. f. Kulturtechnik und Landentwicklung, 1996, 37, 24-31