Dear Author,

Please, note that changes made to the HTML content will be added to the article before publication, but are not reflected in this PDF.

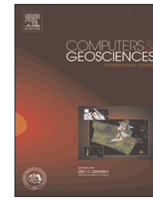
Note also that this file should not be used for submitting corrections.

Computers & Geosciences ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo



Case study

# *soilphysics*: An R package to determine soil preconsolidation pressure

Anderson Rodrigo da Silva [a,*], Renato Paiva de Lima [b]

[a] Goiano Federal Institute, Agronomy, Geraldo S. Nascimento Road – Km 2.5, 75790-000 Urutaí, GO, Brazil
[b] Department of Soil Sciences, University of São Paulo – ESALQ/USP, Av. Pádua Dias 11, 13418-900 Piracicaba, SP, Brazil

ARTICLE INFO

*Article history:*
Received 25 September 2014
Received in revised form
25 August 2015
Accepted 26 August 2015

*Keywords:*
Compression curve
Soil mechanics
Casagrande method
Software R

ABSTRACT

Preconsolidation pressure is a parameter obtained from the soil compression curve and has been used as an indicator of load-bearing capacity of soil, as well as to characterize the impacts suffered by the use of machines. Despite its importance in soil physics, there is a few software or computational routines to support its determination. In this paper we present a computational package in R language, the package *soilphysics*, which contains implementations of the main methods for determining preconsolidation pressure, such as the method of Casagrande, Pacheco Silva, regression methods and the method of the virgin compression line intercept. There is still a consensus that Casagrande is the standard method, although the method of Pacheco Silva has shown similar values. The method of the virgin compression line intercept can be used when trying to be more conservative on the value (smaller) of pre-consolidation pressure. Furthermore, Casagrande could be replaced by a regression method when the compression curve is obtained from saturated soils. The theory behind each method is presented and the algorithms are thoroughly described. We also give some support on how to use the R functions. Examples are used to illustrate the capabilities of the package, and the results are briefly discussed. The latter were validated using a recently published VBA. With *soilphysics*, the user has all the graphical and statistical power of R to determine preconsolidation pressure using different methods. The package is distribution free (under the GPL-2|3) and is currently available from the Comprehensive R Archive Network (http://CRAN.R-project.org/package=soilphysics). The R platform and all the package dependencies are similarly available from CRAN.





## 1. Introduction

The emergence of agricultural mechanization provided advances and modernization of agriculture. Today, this is a reflection of technology in the field. With the consolidation of mechanized systems, we started to realize that operations with farm machinery had negative impacts on soil, especially when operated without traffic control (Imhoff et al., 2004; Saffih-Hdadi et al., 2009). The main impact observed in the soil–machine interface is the compression, resulting from a decreased volume of soil mass in response to the imposition of external loads, caused by agricultural traffic (Imhoff et al., 2004; Saffih-Hdadi et al., 2009).

One proposal to determine extent of damage by agricultural traffic in order to avoid compaction is to study the soil compression process. It is characterized by compressibility tests, whose results are analyzed using a compression curve (Keller and Lamandé, 2010; Keller et al., 2011). The latter reflects the history of stresses experienced by the soil and is used as an indicator of load-bearing capacity of soil, as well as to characterize the impacts suffered by the use of the machines (Casagrande, 1936; Baumgartl and Köck, 2004; Imhoff et al., 2004; Saffih-Hdadi et al., 2009).

The pre-consolidation pressure is obtained from a compression curve. According to Imhoff et al. (2004), in practice, the agricultural traffic control by use of information on the pre-consolidation pressure can be made when the machine load and the tire inflation pressure applied on soil do not exceed the value of pre-consolidation pressure. Thus, the pre-consolidation pressure can be seen as the load bearing capacity of soil.

Using a mathematical definition, pre-consolidation pressure is the point that divides the compression curve into two segments. The first part is the portion of the curve corresponding to elastic deformations (recoverable). The second part is called *virgin compression curve*, corresponding to plastic deformations (irreversible) (Casagrande, 1936; Baumgartl and Köck, 2004; Dias Junior and Pierce, 1995). The region of the curve corresponding to elastic deformation can be used to determine the appropriate time at which the soil must be mobilized or trafficked without occurrence of any additional compaction (Dias Junior and Pierce, 1995). This is because it is this component of the compression curve that reflects the soil stress history (Baumgartl and Köck, 2004). Thus, the

* Corresponding author.
*E-mail address:* anderson.silva@ifgoiano.edu.br (A.R. da Silva).

http://dx.doi.org/10.1016/j.cageo.2015.08.008
0098-3004/© 2015 Published by Elsevier Ltd.

highest pressure that can be applied on soil to prevent compaction is the pre-consolidation pressure (Dias Junior and Pierce, 1995; Baumgartl and Köck, 2004; Imhoff et al., 2004; Saffih-Hdadi et al., 2009). Therefore, it has been widely used for the control of agriculture, based on traffic data for various management classes and ground systems worldwide.

There are several determination methods of pre-consolidation pressure, such as the method proposed by Casagrande (1936), Pacheco Silva (ABNT, 1990), the regression methods presented by Dias Junior and Pierce (1995) and the method suggested by Arvidsson and Keller (2004). Some comparison results can be found in the works of Gregory et al. (2006), Cavalieri et al. (2008) and Rosa et al. (2011). Moreover, Cavalieri et al. (2008) analyzed the results obtained with the methods of Casagrande, regression methods based on the first 2 and 3 points of the compression curves and the method proposed by Arvidsson and Keller (2004) on the same compression curve.

The determination of the pre-consolidation pressure by any method requires mathematical manipulation of the compression curve, which may be facilitated by means of computer programs. However, there are only a few computational environments that assist the calculations of pre-consolidation pressure through the underlying methods. One of them is a Visual Basic Application developed by Gubiani et al. (2014).

The software R (R Core Team, 2014) is a distribution-free computing environment that receives contributions from researchers and experts in various fields of science worldwide. Notwithstanding, packages destined for soil science are scarce (Omuto and Gumbe, 2009) and there is still no package that can deal with pre-consolidation pressure.

In this paper we present and illustrate the capabilities of the R package *soilphysics*, version 2.4, in determining preconsolidation pressure using the methods of Casagrande (1936), Pacheco Silva (ABNT, 1990), the regression methods presented by Dias Junior and Pierce (1995) and the method presented by Arvidsson and Keller (2004). Graphics and simple outputs facilitate the understanding of each method.

## 2. Methods principles

### *2.1 Casagrande (1936) method*

The Casagrande method is widely accepted and used as a standard method for determining the pre-consolidation pressure ($\sigma_p$) in studies of comparison of methods. To obtain the Casagrande method, the compression curve can be modeled by a polynomial of a higher degree (usually four or five) and by the van Genuchten (1980) equation (Cavalieri et al., 2008). After fitting the model, the $\sigma_p$ value can be obtained using the following algorithm:

i. Determine the maximum curvature point of the curve in a $\log_{10}$ scale;
ii. Draw a parallel line to the *x*-axis and a tangent line from this point, in order to obtain a bisector of the angle formed by these lines;
iii. The intersection between the bisector and the extension of virgin compression line defines the value of $\sigma_p$ on the *x*-axis.

An illustration of the method is shown in Fig. 1.

### *2.2 Pacheco Silva (ABNT, 1990) method*

The Pacheco Silva method was published by Associação Brasileira de Normas Técnicas – ABNT (1990). The $\sigma_p$ value can be obtained using the algorithm:

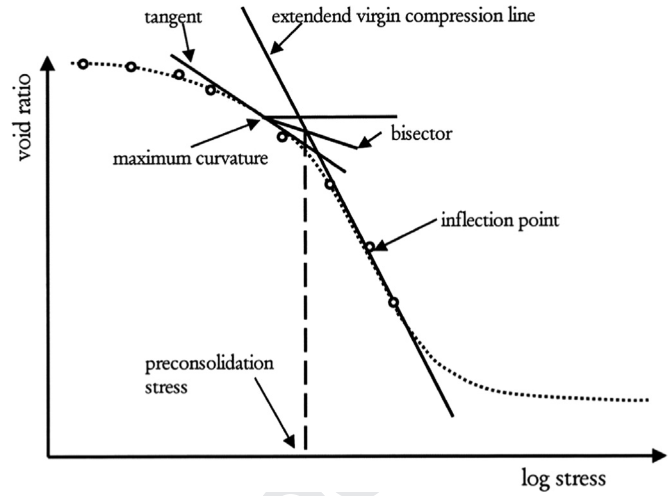



**Fig. 1.** Pre-consolidation pressure through Casagrande (1936) method. (Extracted from Baumgartl and Köck (2004)).

i. Extend the virgin compression line until it intercepts the horizontal axis corresponding to the initial void ratio;
ii. From the intersection point, move down a vertical line until the compression curve is reached;
iii. From this point, draw a horizontal line to the extension of the virgin compression line;
iv. The intersection between the horizontal to the extension of the virgin compression line defines the position of $\sigma_p$.

### *2.3 Regression methods*

In their work, Dias Junior and Pierce (1995) presented a theory for calculating the $\sigma_p$ using regressions that intersect the virgin curve by different numbers of points. The $\sigma_p$ value can be obtained with the following algorithm:

i. A regression line is drawn considering 2, 3, 4 or 5 points at the part of the curve that corresponds to deformations;
ii. The virgin compression line is extended;
iii. The intercept of the virgin compression line with the regression line defines the position of $\sigma_p$.

### *2.4 Arvidsson and Keller (2004) method*

Arvidsson and Keller (2004) presented another way of calculating $\sigma_p$, the fundamental aspects of which can be found in their work. The pre-consolidation pressure value is calculated with the following algorithm:

i. Extend the virgin compression line until it intercepts a horizontal line drawn from the initial void ratio;
ii. The point defined by the abscissa intercept of virgin compression line with the horizontal line drawn from the initial void ratio defines the position of $\sigma_p$.

## 3. Calculation of $\sigma_p$ in *soilphysics*

When loading *soilphysics* (type `library(soilphysics)`), the following packages are required: *MASS* (Venables and Ripley, 2002) and *rpanel* (Bowman et al., 2007). The first is called by the function `simSigmaP()`, which has been designed to simulate preconsolidation pressure. Currently, the functionalities of *rpanel* are used only when fitting soil water models.

In the *soilphysics* manual (Silva and Lima, 2015), the user will find a list of functions, including the `sigmaP()` function, which determines the $\sigma_p$, in accordance with the following command:

```
R> sigmaP(voidratio, stress, method, n4VCL, mcp)
```

where,

- `voidratio` A numeric vector containing void ratio values.
- `method` A character indicating which method is to be computed.
- `n4VCL` The number of points for calculating the slope of the soil Virgin Compression Line (VCL), which is obtained by linear regression.
- `mpc` The maximum curvature point in $\log_{10}$ scale of stress; required only if the method “casagrande” is used.
- `graph` Logical; if TRUE (default) the compression curve is plotted.

In the argument `method`, the user can enter the method with which they wish to calculate $\sigma_p$, with the following being available:

| | |
|---|---|
| `"casagrande"` | Casagrande (1936) |
| `"pacheco"` | Pacheco Silva (ABNT, 1990) |
| `"VCLzero"` | Arvidsson and Keller (2004) |
| `"reg1", "reg2", "reg3", "reg4"` | Dias Junior and Pierce (1995) |

In particular, for the Casagrande method, the user has two options. First, the point of maximum curvature can be entered directly into the `mpc` argument, in log10 scale, as proposed by Casagrande (1936), with which the point of maximum curvature of the compression curve is arbitrarily chosen. The boundaries for the `mpc` argument in `sigmaP()` are 0,0 and 3,2, corresponding to the following $\log_{10}$ scaled values: 1,0 and 1600 kPa, usually taken as a range of applied pressure in soil compression tests.

In the second option, `sigmaP()` will automatically calculate the maximum curvature point using the third derivative (Appendix A.1.1) of a fourth degree polynomial function modeling the compression curve, as suggested by Arvidsson and Keller (2004) and Cavalieri et al. (2008).

For determinations by regression methods, the user must choose the number of points that they want to use in the regression intercept virgin compression line. The *soilphysics* fit a simple linear regression model with 2, 3, 4 or 5 starting points of the curve, as shown by Dias Junior and Pierce (1995).

In all of the methods available to the user, there is the option to choose the number of points for the adjustment of the linear virgin compression through `n4VCL` argument, which defaults to 3, thus using the last three points of the curve.

In `sigmaP()`, the function is required to be a numerical input vector containing values of the void ratio. If the user does not have a void ratio, this can be calculated using the `voidratio()` function. In this case, it is assumed that the user only has data relating to the sample used in the compression test (strain data). The vector containing the void ratio can be obtained as follows:

```
R> voidratio(wetsoil, drysoil, diam.cylinder,
+ height.cylinder, dens.particle, deformation)
```

where,

- wetsoil The weight of wet soil
- drysoil The weight of dry soil
- diam.cylinder The diameter of the cylinder
- height.cylinder The height of the cylinder
- dens.particle The particle density value
- deformation A numeric vector containing soil deformation values

The flow chart calculate of pre-consolidation pressure in *soilphysics* is illustrated in Fig. 2.

## 4. Examples

Considering the results of a compression test (Table 1), we can observe the values of the void ratio after each stress applied.

In the R console, the data must be entered as two vectors: one containing applied stress and the other containing void ratio. Then, we can use the function `sigmaP()` to perform the calculations according to the method chosen. For example, for determining $\sigma_p$ using the Casagrande method, type:

```
R> pres <- c(1, 12.5, 25, 50, 100, 200, 400, 800, 1600)
R> VR <- c(0.846, 0.829, 0.820, 0.802, 0.767, 0.717, 0.660, 0.595, 0.532)

R> sigmaP(VR, pres, method = "casagrande", mcp = 1.6)
```

Note that, although `sigmaP()` can automatically determine the maximum curvature point when the Casagrande method is being used, we chose to pass the argument `mcp`. We used the value 1.6. A good guide for this value is a graphical analysis, using the command:

```
R> plot(log10(pres), VR)
```

The result is the first plot (top left) shown in Fig. 3.

If the user does not have the void ratios, but only the compression test data, it is still possible to calculate $\sigma_p$. Consider for example the data presented in Table 2.

In this case, the calculation of $\sigma_p$ depends on the calculation of void ratios. It can be done with the function `voidratio()`, as follows:

```
R> def <- c(0, 0.0230, 0.0352, 0.0605, 0.1070, 0.1750, 0.2525, 0.3395, 0.4250)
R> pres <- c(1, 12.5, 25, 50, 100, 200, 400, 800, 1600)
R> VR <- voidratio(wetsoil = 170.62, drysoil = 134.08, diam.cylinder = 6.95, height.cylinder = 2.5, dens.particle = 2.61, def)
```

The object `VR` contains the same values (rounded) of void ratio presented in Table 1. Thus, the pre-consolidation pressure through Casagrande method is calculated as indicated early, using `sigmaP()`.

## 5. Results and discussion

The results of the calculations performed using with the

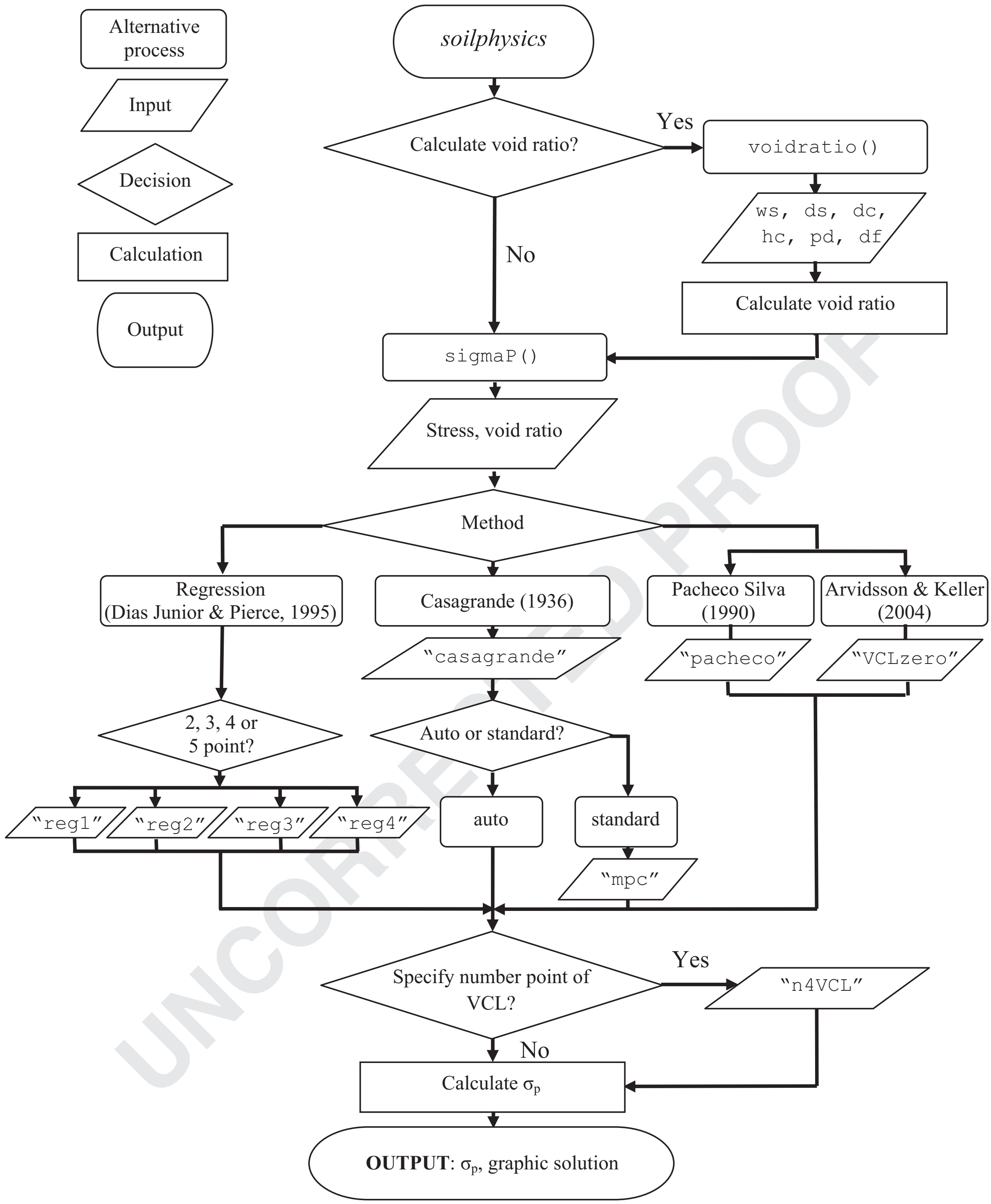



**Fig. 2.** The flow of the pre-consolidation pressure in *soilphysics*. `ws` – the weight of wet soil; `ds` – the weight of dry soil; `dc` – the diameter of the cylinder; `hc` – the height of the cylinder; `pd` – the particle density; `df` – a numeric vector containing soil deformation values; $\sigma_p$ – pre-consolidation pressure; VCL – Virgin Compression Line.



**Table 1**
Data set containing values of stress (kPa) and soil void ratio.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Stress (kPa) | 1 | 12.5 | 25 | 50 | 100 | 200 | 400 | 800 | 1600 |
| Void ratio | 0.846 | 0.829 | 0.820 | 0.802 | 0.767 | 0.717 | 0.660 | 0.595 | 0.532 |

examples from Tables 1 and 2 are shown in Table 3, for each method available in `sigmaP()`. The graphical output illustrating the calculations is shown in Fig. 3.

Note that different methods promote different values of $\sigma_p$. For example, Dias Junior and Pierce (1995) analyzed and compared Casagrande with regression methods and checked that their agreement decreases as the number of points used by the regression method gets increased. The correlations of the regression methods based on two, three and four points with Casagrande method were of 0.87, 0.80 and 0.71, respectively.

In other studies Arvidsson and Keller (2004) and Cavalieri et al. (2008) analyzed different methods to calculate $\sigma_p$. In both studies

Please cite this article as: da Silva, A.R., de Lima, R.P., *soilphysics*: An R package to determine soil preconsolidation pressure. Computers & Geosciences (2015), http://dx.doi.org/10.1016/j.cageo.2015.08.008

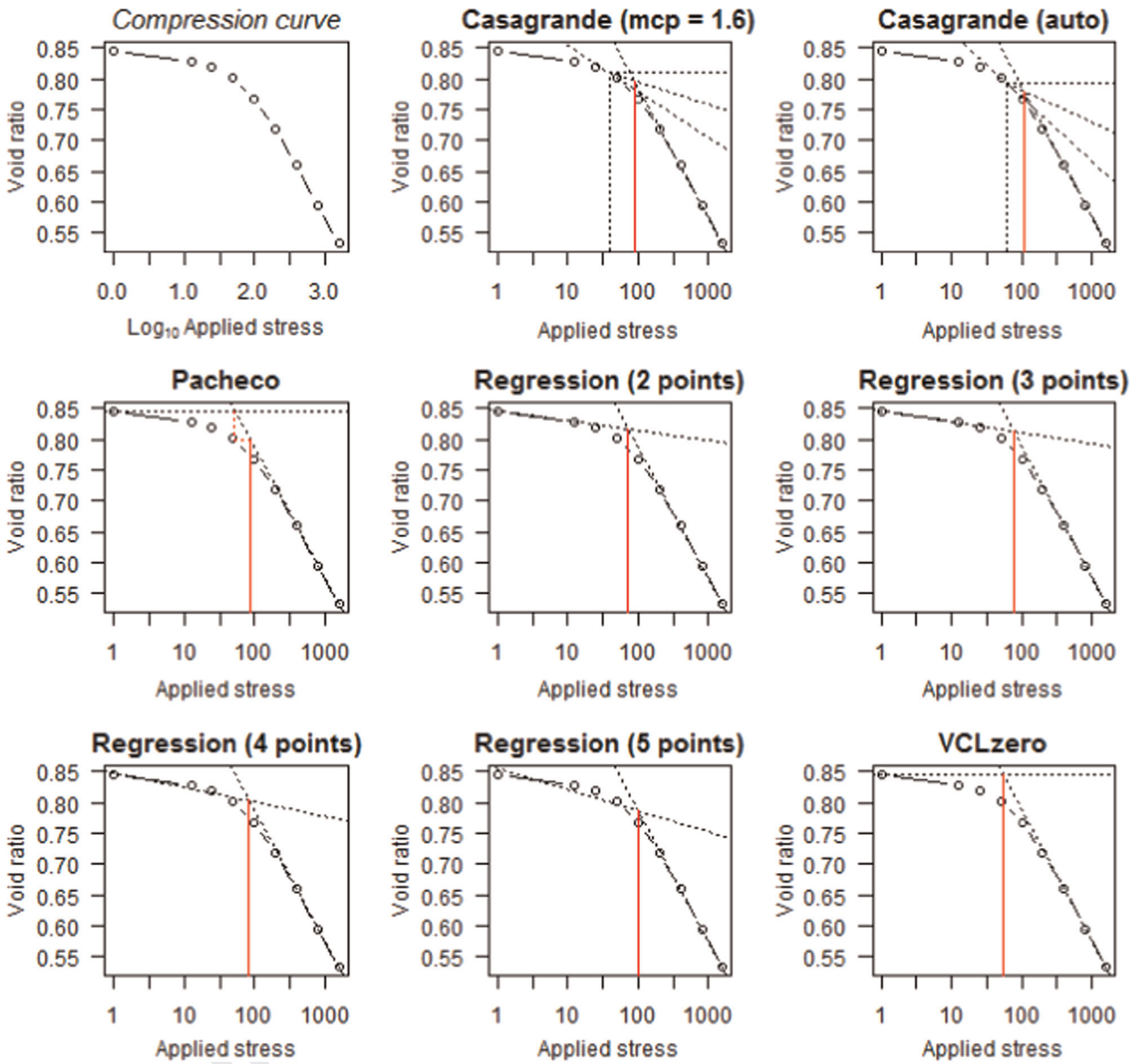



**Fig. 3.** Graphical output of the function `sigmaP()` from the data given in Tables 1 and 2. Vertical dotted lines in Casagrande method represents the maximum curvature points (mcp) and the red line corresponds to the pre-consolidation pressure.

the authors considered Casagrande method (polynomial fit) as the standard and used it to evaluate other methods. The correlation values between Casagrande and regression methods based on two and three points were in the range 0.60–0.70, as found by Arvidsson and Keller (2004); likewise, Cavalieri et al. (2008) found values ranging from 0.65 to 0.77. Rosa et al. (2011) stated that the values obtained using the method of Pacheco Silva are similar to those obtained with the Casagrande method.

According to Arvidsson and Keller (2004) the VCLzero method was considered by McBride and Joosse (1996) as a "conservative"

**Table 3**
Values of $\sigma_p$ (kPa) using the data from Tables 1 and 2.

| Casagrande (mcp = 1.6) | Casagrande "auto" | Pacheco | reg1 | reg2 | reg3 | reg4 | VCLzero |
|---|---|---|---|---|---|---|---|
| 91.1 | 108.7 | 87.8 | 71.7 | 75.0 | 83.4 | 100.7 | 52.5 |

**Table 2**
Data of a compression test.

| Stress (kPa) | 1 | 12.5 | 25 | 50 | 100 | 200 | 400 | 800 | 1600 |
|---|---|---|---|---|---|---|---|---|---|
| Deformation (cm) | 0 | 0.0230 | 0.0352 | 0.0605 | 0.1070 | 0.1750 | 0.2525 | 0.3395 | 0.4250 |

| Height of the cylinder (cm) | Diameter of the cylinder (cm) | Weight of wet soil (g) | Weight of dry soil (g) | Particle density (Mg m$^{-3}$) |
|---|---|---|---|---|
| 2.50 | 6.95 | 170.62 | 134.08 | 2.61 |

or "minimum possible" $\sigma_p$ value. Therefore, the VCLzero method can be used when trying to be more conservative, because in general the values are much lower (Arvidsson and Keller, 2004; Rosa et al., 2013) than the other methods, such as those in Table 3.

Despite the availability of different methods, most of the researches, such as Dias Junior and Pierce (1995), Arvidsson and Keller (2004), Cavalieri et al. (2008), have taken Casagrande as the standard method.

Especially about the Casagrande method, Cavalieri et al. (2008) explain that the determination of the maximum curvature point (mcp) is often subjective, although the original method was proposed this way. The authors have recommended the determination of mcp mathematically, thus avoiding the subjectivity. Dias Junior and Pierce (1995) explained that when using undisturbed soil samples, the selection of the point of minimum radius can be difficult in high soil water content because the compression curve is almost linear. The same observation was given by Arvidsson and Keller (2004), remarking a very strong influence of water tension on $\sigma_p$ when it is calculated through the Casagrande method. In this case, Dias Junior and Pierce (1995) suggested that Casagrande would be replaced by a regression method.

We compared the results obtained by *soilphysics* with those obtained using the VBA developed by Gubiani et al. (2014), containing the following methods: Casagrande (with automatic calculation of mcp), reg1, reg2, reg3 and reg4. For the methods of Pacheco and VCLzero we have found no software or published routine. Using the data from Table 2, comparison results are shown in Table 4. Note that the codes used to calculate $\sigma_p$ using Casagrande method in *soilphysics* are exactly the same used for obtaining the results in Table 3. However, for calculating $\sigma_p$ through the regression methods, we considered only the values of applied stress starting from 12.5 kPa, as does the Visual Basic program, although it receives all the values of applied stress as input. In *soilphysics*, the use of the initial value of applied stress is an option of the user.

Despite modeling the compression curve using van Genuchten (1980) model when the Casagrande method is chosen, results obtained by both computational resources are essentially the same, with a negligible difference. We observed similar results when using regression methods.

## 6. Conclusions

With *soilphysics* it is possible to determine the preconsolidation pressure using the methods of Casagrande, Pacheco Silva, four regression methods and the method of the virgin compression line intercept. Casagrande is considered the standard method.

The package produces graphics with high quality that illustrate the process of preconsolidation pressure determination and may be used for subsequent publication in scientific journals and reports. *soilphysics* is distribution free (under the GPL-2|3) and is currently available from the Comprehensive R Archive Network (http://CRAN.R-project.org/package=soilphysics). The R platform and all the package dependencies are similarly available from CRAN.

**Table 4**
Values of preconsolidation pressure calculated using *soilphysics* and a Visual Basic program by Gubiani et al. (2014).

| Program | Casagrande "auto" | reg1 | reg2 | reg3 | reg4 |
|---|---|---|---|---|---|
| *soilphysics* | 108.7 | 82.4 | 96.7 | 123.4 | 170.5 |
| Visual basic | 107.3 | 81.4 | 96.1 | 121.9 | 169.6 |

Currently, the model available in *soilphysics* for modeling compression curves is only the fourth-degree polynomial function. The van Genuchten (1980) and Gompertz models, as used by Gregory et al. (2006), may be implemented in future versions.

## Uncited reference

Lozano et al. (2013).

## Acknowledgments

We thank the Coordination for Improvement of Higher Level Personnel (CAPES, Brazil) for granting scholarships, and the Goiano Federal Institute (Brazil) for the financial support.

## Appendix A. Casagrande (1936) method

### A.1. Fourth degree polynomial model

Function:

$$v = f(s) = \beta_0 + \beta_1 \log s + \beta_2 (\log s)^2 + \beta_3 (\log s)^3 + \beta_4 (\log s)^4 + \varepsilon \quad \text{(A1)}$$

where $v$ is the void ratio, $s$ is the applied stress (kPa), $\beta_0$, $\beta_1$, $\beta_2$, $\beta_3$ and $\beta_4$ are the parameters of the model and $\varepsilon$ is a random variable.

First derivative:

$$\frac{dv}{d \log s} = f'(s) = \beta_1 + 2\beta_2 \log s + 3\beta_3 (\log s)^2 + 4\beta_4 (\log s)^3 \quad \text{(A2)}$$

Second derivative:

$$\frac{d^2 v}{d(\log s)^2} = f''(s) = 2\beta_2 \log s + 6\beta_3 \log s + 12\beta_4 (\log s)^2 \quad \text{(A3)}$$

Third derivative:

$$\frac{d^3 v}{d(\log s)^3} = f'''(s) = 6\beta_3 + 24\beta_4 \log s \quad \text{(A4)}$$

#### A.1.1. Determination of the maximum curvature point

The $\log_{10}$ stress value corresponding to the maximum curvature point, $\log s_0$, should be indicated by the user. Otherwise, `sigmaP()` then calculates it using the third derivative of the fourth-degree polynomial function, i.e., by setting it to be null. Then,

$$mcp = \log s_0 = \frac{-\beta_3}{4\beta_4} \quad \text{(A5)}$$

#### A.1.2. Tangent to the function at the maximum curvature point

$$g(s) = f(s_0) + f'(s_0) \log\left(\frac{s}{s_0}\right) \quad \text{(A6)}$$

#### A.1.3. Bisector between the tangent and a horizontal line

$$h(s) = f(s_0) + 0.5 f'(s_0) \log\left(\frac{s}{s_0}\right) \quad \text{(A7)}$$

*A.1.4. Calculation of the preconsolidation pressure*

Consider $l(s) = b_0 + b_1 \log s + \varepsilon$ as the model of the virgin compression line (VCL). Then, take

$$\hat{\sigma}_P = \frac{\hat{b}_0 - \left[f(s_0) - 0.5f'(s_0)\log s_0\right]}{0.5f'(s_0) - \hat{b}_1} \tag{A8}$$

as the estimate of the preconsolidation pressure.

## Appendix B. Pacheco Silva (ABNT, 1990) method

Consider $l(s) = b_0 + b_1 \log s + \varepsilon$ as the model of the virgin compression line (VCL). Calculate a $\log s$ value, $x_0$, that represents the interception between VCL and a horizontal line from the initial value of void ratio ($v_1$):

$$x_0 = \frac{v_1 - \hat{b}_0}{\hat{b}_1} \tag{B1}$$

Then, take

$$\hat{\sigma}_P = \frac{f(x_0) - \hat{b}_0}{\hat{b}_1} \tag{B2}$$

as the estimate of the preconsolidation pressure, where $f(.)$ is the model defined in A1.

## Appendix C. Regression methods

Consider $l(s) = b_0 + b_1 \log s + \varepsilon$ as the model of the virgin compression line (VCL) and $k(s) = a_0 + a_1 \log s + \varepsilon$ as the model of the initial compression line, based on 2, 3, 4 or 5 initial values of void ratio. Then, take

$$\hat{\sigma}_P = \frac{\hat{b}_0 - \hat{a}_0}{\hat{a}_1 - \hat{b}_1} \tag{C1}$$

as the estimate of the preconsolidation pressure.

## Appendix D. Arvidsson and Keller (2004)

Consider $l(s) = b_0 + b_1 \log s + \varepsilon$ as the model of the virgin compression line (VCL) and $v_1$ as the void ratio value at zero strain. Then, take

$$\hat{\sigma}_P = \frac{v_1 - \hat{b}_0}{\hat{b}_1} \tag{D1}$$

as the estimate of the preconsolidation pressure, where $f(.)$ is the model defined in A1.

Part of this appendix was adapted from Arvidsson and Keller (2004) and Cavalieri et al. (2008).

## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.cageo.2015.08.008.

## References


Arvidsson, J., Keller, T., 2004. Soil precompression stress. I. A survey of Swedish arable soils. Soil Tillage Res. 77, 85–95.

Associação Brasileira de Normas Técnicas – ABNT, 1990. NBR 12007: Ensaio de adensamento unidimensional. Rio de Janeiro. 13 pp.

Baumgartl, T., Köck, B., 2004. Modeling volume change and mechanical properties with hydraulic models. Soil Sci. Soc. Am. J. 68, 57–65.

Bowman, A., Crawford, E., Alexander, G., Bowman, R.W., 2007. rpanel: simple interactive controls for R functions using the tcltk package. J. Stat. Softw. 17, 1–18.

Casagrande, A., 1936. Determination of the pre-consolidation load and its practical significance. In: Proceedings of the International Conference on Soil Mechanics and Foundation Engineering, vol. III, Harvard University, Cambridge, MA, pp. 60–64.

Cavalieri, K.M.V., Arvidsson, J., Silva, A.P., Keller, T., 2008. Determination of precompression stress from uniaxial compression tests. Soil Tillage Res. 98, 17–26.

Dias Junior, M.S., Pierce, F.J., 1995. A simple procedure for estimating preconsolidation pressure from soil compression curves. Soil Technol. 8, 139–151.

Gregory, A.S., Whalley, W.R., Watts, C.W., Bird, N.R.A., Hallett, P.D., Whitmore, A.P., 2006. Calculation of the compression index and pre-compression stress from soil compression test data. Soil Tillage Res. 89, 45–57.

Gubiani, P.I., Reinert, D.J., Reichert, J.M., Goulart, R.Z., Fontanela, E., 2014. Suplemento excel para modelar a curva de compressão do solo. In: XX Congreso Latinoamericano y XVI Congreso Peruano de la Ciencia del Suelo. Cusco.

Imhoff, S., Silva, A.P., Fallow, D., 2004. Susceptibility to compaction, load support capacity, and soil compressibility of Hapludox. Soil Sci. Am. J. 68, 17–24.

Keller, T., Lamandé, M., 2010. Challenges in the development of analytical soil compaction models. Soil Tillage Res. 111, 54–64.

Keller, T., Lamandé, M., Schϕjnning, P., Dexter, A.R., 2011. Analysis of soil compression curves from uniaxial confined compression tests. Geoderma 163, 13–23.

Lozano, N., Rolim, M.M., Oliveira, V.S., Tavares, U.E., Pedrosa, E.M.R., 2013. Evaluation of soil compaction by modeling field vehicle traffic with SoilFlex during sugarcane harvest. Soil Tillage Res. 129, 61–68.

McBride, R.A., Joosse, P.J., 1996. Overconsolidation in agricultural soils. II. Pedotransfer functions for estimating preconsolidation stress. Soil Sci. Am. J. 60, 373–380.

Omuto, C.T., Gumbe, L.O., 2009. Estimating water infiltration and retention characteristics using a computer program in R. Comput. Geosci. 35, 579–585.

Core Team, R., 2014. R: A Language and Environment for Statistical Computing.. R Foundation for Statistical Computing, Vienna, Austria, ISBN: 3-900051-07-0. Available from: /⟨http://www.R-project.org⟩.

Rosa, D.P., Reichert, J.M., Mentges, M.I., Vieira, D.A., Vogelman, E.S., Rosa, V.T., Reinert, D.J., 2011. Estimation methods of soil load support capacity of a Hapludalf. Rev. Bras. Cienc. Solo 35, 1561–1568 (in Portuguese, with abstract in English).

Saffih-Hdadi, K., Défossez, P., Richard, G., Cui, Y.J., Tang, A.M., Chaplain, V.A., 2009. Method for predicting soil susceptibility to the compaction of surface layers as a function of water content and bulk density. Soil Tillage Res. 105, 96–103.

Silva, A.R., Lima, R.P., 2015. soilphysics: Soil Physical Analysis. R package version 2.4. Available from: ⟨http://CRAN.R-project.org/package=soilphysics⟩.

van Genuchten, M.T., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S, fourth edition. Springer, New York.




Please cite this article as: da Silva, A.R., de Lima, R.P., *soilphysics*: An R package to determine soil preconsolidation pressure. Computers & Geosciences (2015), http://dx.doi.org/10.1016/j.cageo.2015.08.008