



# SO-Consolidation

Version 1.0.7889.1

## Scientific Manual

This software is developed by Soil Office Software Group and is aimed at the evaluation of one-dimensional consolidation tests.

Various methods can be used and sensitivity analysis can be performed on the results; These smart capabilities lead to much better and more precise analyzes on the tests. In addition to test data and corresponding calculations, software outputs are presented in both landscape and portrait formats.



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## **1 INTRODUCTION**

### **1-1 SOIL OFFICE**

“Soil Office” is a developer of geotechnical engineering software since 2013. Our main objective is to develop functional and user friendly software, capable of performing precise calculations. The following software is currently considered:

- SO-Foundation: Bearing capacity of shallow foundations
- SO-Lab: Soil mechanics laboratory tests and boring logs including:
  - SO-Sieve: Sieve analysis, Hydrometer & Atterberg limits
  - SO-Shear: Direct shear
  - SO-Unconfined: Unconfined compression
  - SO-Triaxial: Triaxial compression
  - SO-Consolidation: One-dimensional consolidation
  - SO-Log: Geotechnical engineering boring logs

Feel free to contact us regarding any criticism, recommendation or additional information.

### **1-2 SO-CONSOLIDATION**

SO-Consolidation is aimed at the evaluation of one-dimensional consolidation tests. Individual tabs are assigned for project information (including basic information, borings and samples) and tests. In addition to test data and corresponding calculations, software outputs are presented in both landscape and portrait formats.

In order to obtain coefficient of consolidation and secondary compression index, each loading step can be analyzed by two methods; logarithm and square root of time. Also, the Casagrande and the simplified methods can be employed for the determination of final results including preconsolidation stress and compression and swelling indices. Each interpretation method is accompanied by a variety of capabilities and in addition to being automatic, can be modified by the user.

Note that consolidation tests could randomly be generated (including dial-time readings of each loading step) based on user-defined criteria.

## 1-3 SOFTWARE CAPABILITIES

### 1-3-1 GENERAL FEATURES

- User is informed about the common ranges regarding input parameters.
- Separate outputs are considered regarding the “whole test” and the “loading steps”.
- Software outputs are exported in both landscape and portrait formats.
- Test data and corresponding calculations are presented in a separate format.
- Blank laboratory data sheets may be used for test data input.
- Saving files with a minimal size.

### 1-3-2 CONSOLIDATION TEST CALCULATIONS

- Implemented evaluation methods are beyond ASTM D2435.
- Interpretation methods are automatically applied and can be modified by the user.
- Test data can be edited using either graphs or input tables.

#### ❖ Loading steps

- Logarithm and square root of time methods are implemented.
- Sensitivity analysis can be performed on the degree of consolidation parameter, leading to much better and more precise determination of the coefficient of consolidation.
- Consolidation tests could randomly be generated based on user-defined criteria including:
  - Settlement percentage regarding each of the steps (elastic, primary consolidation and secondary consolidation)
  - Dial reading times

#### ❖ Whole test

- The Casagrande and the simplified methods are employed.
- Consolidation tests could randomly be generated based on user-defined criteria including:
  - Loading schedule and corresponding apparatus calibration
  - Initial dial reading and its trend (increase or decrease)
  - Preconsolidation stress and compression and swelling indices

## 2 SOFTWARE INTERFACE

### 2-1 GENERAL

After running SO-Consolidation, the following menus are visible on the top ribbon:

**File menu:** Contains commands relating to the handling of files, such as creating a new project, save, etc.

**Main:** Project information, borings and samples are determined using this menu.

**Test:** Contains the following:

- **One-dimensional consolidation:** Is aimed at the evaluation of consolidation tests.
- **Edit:** Tests performed on a sample can be copied, moved or deleted using this menu.

**Export:** Contains the following:

- **Export:** Is used to export software outputs.
- **Blank:** Includes blank laboratory data sheets.

**Settings:** Program settings are determined through this menu.

**Help:** Contains the following:

- **Scientific manual:** Describes functionality of different parts of the software and the theories of the utilized methods.
- **Index:** Contains indexed help topics.

**License:** The permit to use the software and information on the client.

**About:** Contains general information.

- **SO-Consolidation:** Brief description about the current software and its version.
- **Soil Office:** Introducing Soil Office Software Group.

**Units:** Interactively switches between the available unit systems.

## 2-2 DETAILS ON MENUS

### 2-2-1 FILE MENU

This menu is consisted of the following:

**New:** Creation of a new project.

**Open:** Opens a previously defined project.

**Save:** Saves project (with \*.soc extension).

**Save as:** Saves project with a different name.

**Sample project:** Sample project in order to demonstrate software features and easily work with it. A number of consolidation tests have been calculated or generated by a variety of methods.

**Close:** Closes project.

**Exit:** Closes project and exits SO-Consolidation.

### 2-2-2 MAIN

#### 2-2-2-1 PROJECT INFORMATION

Basic project information including name, client, location and code are entered in this section. A separate field is also dedicated for notes. The user can specify the project location on the map and the coordinates will be shown in the corresponding field. Project address is also presented by activating the “Reverse geocoding” option and the user may accept it or not.

#### 2-2-2-2 TABLE OF BORINGS

Project borings are identified through this table. The input parameters are listed below:

**Boring method:** Whenever the boring is machine-drilled and the method is not included in the available options or the user prefers it not to be specified, the “-” option can be used.

**Name:** Boring name.

**Depth:** Boring depth.

**Elev.:** Ground elevation at top of boring.

**GWT:** Depth to water table measured from boring top (Ground Water Table).

**Note:** Notes regarding the boring such as weather conditions including recent rain or other events that could affect subsurface conditions.

**Export:** Defines whether the boring is included in the output or not. This option is active by default.

**Contractor:** Name of the drilling contractor.

**Start date:** Start date of drilling.

**Finish date:** Finish date of drilling.

The up and down arrows located on the right side of the table, are for the purpose of altering the order of the borings.

### 2-2-2-3 TABLE OF SAMPLES

Samples obtained within each of the borings are introduced in this table. The input parameters are listed below:

Depth: Sample depth.

USCS: Soil type according to USCS (Unified Soil Classification System).

Sample category: Sample category including “Disturbed”, “Undisturbed” and “Rock core”.

Sample type: varies by boring method and sample category. “-” may be used if empty for any reason.

Color: Sample color. Some colors are available by default and others can be defined by the user.

Code: Sample code.

Note: Notes regarding sample or its extrusion process.

### 2-2-3 TEST

#### 2-2-3-1 ONE-DIMENSIONAL CONSOLIDATION

SO-Consolidation is aimed at the evaluation of consolidation tests and can be used in the following modes:

- Test data: are entered and calculations are performed.
- Generation: This option is mainly for the generation of random consolidation tests (including dial-time readings of each loading step) based on user-defined criteria.

Note that the mentioned modes are selectable using the radio buttons available in the “Whole Test” and “Loading Steps” sections.

##### 2-2-3-1-1 TEST DATA

This option is active by default. Various sections are considered for the input and evaluation of test data which are described below:

##### ❖ Whole Test

This section includes whole test data except dial-time readings of the loading steps and is consisted of the following:

##### ***Sample properties***

Sample properties are determined through this section.

“Start” and “end” of the test:

- $(H)_{st}$  &  $(H)_{en}$ : Height.
- $(M_T)_{st}$  &  $(M_T)_{en}$ : Moist mass.
- $(\gamma_d)_{st}$  &  $(\gamma_d)_{en}$ : Dry unit weight.
- $(w)_{st}$  &  $(w)_{en}$ : Moisture content.
- $(e)_{st}$  &  $(e)_{en}$ : Void ratio.
- $(S)_{st}$  &  $(S)_{en}$ : Saturation.

Constant:

- $D$ : Sample diameter.
- $G_s$ : Specific gravity of soil solids.
- $M_s$ : Weight of soil solids.
- $H_s$ : Equivalent height of soil solids.



### *Above the table*

This section is consisted of the following:

Gauge factor, 1 div.: Coefficient regarding the input of dial readings.

Drainage: Drainage type; single or double.

Dial trend: Dial trend as the settlement increases.

Load apparatus calibration: Using this option, various loading schedules along with corresponding apparatus calibrations can be loaded. Note that the current option is available only when the “d” column in the test table is empty.

### *Test table*

Table columns are as follows:

$P$ : Vertical stress.

$\Delta_a$ : Apparatus calibration.

*Dial*:

$d$ : Dial reading.

$d_c$ : Corrected dial reading.

$\Delta H$ : Height change.

$H$ : Height.

$\varepsilon$ : Vertical strain.

$e$ : Void ratio.

$m_v/m_{vr}$ : Coefficient of volume (re)compressibility.

The “More ...” option, available below the test table, is displayed in red when filled and contains:

Date: Test date.

Time: Test time.

Tested by: Name of the technician.

Note: Notes regarding the test.

❖ Loading steps

The table in this section is dedicated to dial-time readings of the loading steps and contains the following columns:

*Time*: Elapsed time.

*Dial*:

*d*: Dial reading.

*d<sub>c</sub>*: Corrected dial reading.

Note that “Delete readings” is used to delete dial-time readings of the step.

❖ Graph – Whole Test

This section contains test summary graph and the tools for analyzing it. In the current software, the “Casagrande” and the “Simplified” methods are implemented in order to evaluate the parameters below:

*P'<sub>c</sub>*: Effective preconsolidation stress.

*C<sub>c</sub>*: Compression index.

*C<sub>s</sub>*: Swelling index.

Tools and options regarding the mentioned methods are presented in chapter 4 (section 4-4-1) along with the calculation theories.

❖ Graph – Loading Steps

Graphs regarding each of the loading steps and the tools for analyzing them are accessible through this section. The available methods (logarithm and square root of time) are beyond ASTM D2435 and result in the following parameters:

*C<sub>v</sub>*: Coefficient of consolidation.

*C<sub>α</sub>*: Secondary compression index.

*r<sub>i</sub>*: Percentage of elastic settlement.

*r<sub>p</sub>*: Percentage of primary consolidation settlement.

*r<sub>s</sub>*: Percentage of secondary consolidation settlement.

Tools and options regarding the mentioned methods are presented in chapter 4 (section 4-4-2) along with the calculation theories.

❖ Results Summary

The results summary of the tests is accessible through this section. The following columns are included in the table:

*BH/TP*: Borehole or test pit name.

*Depth*: Sample depth.

$P'_c$ : Effective preconsolidation pressure.

$C_c$ : Compression index.

$C_s$ : Swelling index.

Note that the sample is reported as “Remolded” by selecting the corresponding option next to the table.

### 2-2-3-1-2 GENERATION

#### ❖ Whole Test

This option is related to the random generation of sample consolidation tests based on user-defined criteria. In addition to sample properties, the following are needed:

$P'_c, C_c, C_s$  & *Dial trend*: are previously defined.

$(d)_{st}$ : Dial reading corresponding to the start of test.

With the above parameters being defined, by every click on “Generate”, a new consolidation test is randomly generated. Considering the fact that there are various methods for the determination of  $P'_c$ ,  $C_c$  and  $C_s$  and are mostly dependent on the engineering judgment, it is the responsibility of the user to define whether the generated test is synced with the initial data or not.

#### ❖ Loading Steps

This option can be used in order to generate sample dial-time readings (based on user-defined criteria) regarding each of the loading steps. The following parameters are needed:

$r_i, r_p$  &  $r_s$ : are previously defined.

$t_{100}$ : Elapsed time corresponding to 100 [%] primary consolidation.

With the above parameters being defined, by every click on “Generate”, a new set of dial-time readings is randomly generated. Considering the fact that there are various methods for the determination of  $C_v$  and  $C_\alpha$  and are mostly dependent on the engineering judgment, it is the responsibility of the user to define whether the generated test is synced with the initial data or not.

### 2-2-3-2 EDIT

Tests performed on a sample can be copied, moved or deleted using this menu.

Whenever the destination sample contains some data, **the user is not asked for overwrite confirmation.** Therefore the user has to be cautious while using this menu.

## 2-2-4 EXPORT

### 2-2-4-1 EXPORT

Is used to export software outputs, including:

Output: Final test results

- Whole Test – Portrait
- Whole Test - Landscape
- Loading Steps

**Note:** Construction lines are also illustrated in the outputs by activating the corresponding option.

Test data: Test data and corresponding calculations

- Whole Test
- Loading Steps

### 2-2-4-2 BLANK

Blank laboratory data sheets are accessible through this menu.

## 2-2-5 SETTINGS

Program settings are determined through this menu and consist of the following:

- Apparatus Calibration: Loading schedule and the corresponding apparatus calibration (calculated as the deflection difference between the apparatus frame and the sample) with the following columns:
  - Stress,  $P$
  - Frame deflection
  - Sample deflection
  - Apparatus calibration,  $\Delta_a$
- Time List.

### 3 ERRORS

Possible errors in the software are divided to primary and secondary errors which are described in the current chapter.

#### 3-1 PRIMARY ERRORS

Whenever wrong or illogical data are entered, the corresponding cells' colors are altered and a message is shown in the bottom ribbon to guide the user. The utilized colors are described below:

**Red:** The cell is empty or of the wrong data type.

**Orange:** The entered valued is not acceptable.

**Green:** Calculations may be performed, but the cell value seems to be illogical.

**Pink:** Demo version limitations.

**Note:** Project data cannot be exported while primary errors (except green type) exist.

#### 3-2 SECONDARY ERRORS

Unlike primary errors, secondary errors do not apply any limitations on exporting project data and are mostly encountered when changes in some data, cause some others to be inaccurate or incompatible. These errors are of 2 types; compatibility and depth:

**Compatibility errors:** Identify incompatibility among input data.

**Depth errors:** Identify errors due to depth values.

Secondary errors have the following advantages:

- Software does not crash.
- All errors regarding each input data are individually specified.

**Note:** By clicking on the error types located beneath the tables, a message is shown and the user is informed about the probable cause (or causes) of the errors.

## 4 CALCULATION THEORIES

In this chapter, brief description regarding one-dimensional consolidation test is presented. Also utilized parameters and the calculation methods (along with software usage) are fully described. Note that all parameters are defined in this chapter for the ease of access and the calculational parameters are marked with an asterisk (\*).

### 4-1 TEST SUMMARY

The one-dimensional consolidation test is for determining the magnitude and rate of consolidation of soil when it is restrained laterally and drained axially while subjected to incrementally applied controlled-stress loading.

During the consolidation test, a soil specimen is restrained laterally and loaded axially with total stress increments. Each stress increment is maintained until excess pore-water pressures are essentially dissipated. Pore pressure is assumed to be dissipated based on the interpretation of time-deformation readings under constant total stress. This interpretation is founded on the assumption that the soil is 100 [%] saturated. Measurements are made of change in the specimen height and these data are used to determine the relationship between the effective axial stress and void ratio or strain. When time-deformation readings are taken throughout an increment, the rate of consolidation is evaluated with the coefficient of consolidation.

## 4-2 SAMPLE PROPERTIES

Parameters regarding sample dimensions and properties during the test are identified in the following table:

Table 4-1 – Sample dimensions and properties during consolidation test

Description	Diameter	Specific gravity of soil solids	Equivalent height of soil solids	Weight of soil solids	Height	Moist mass	Dry unit weight	Moisture content	Void ratio	Saturation
Start of test	$D$	$G_s$	$H_s$	$M_s$	$(H)_{st}$	$(M_T)_{st}$	$(\gamma_d)_{st}$	$(w)_{st}$	$(e)_{st}$	$(S)_{st}$
End of test					$(H)_{en}$	$(M_T)_{en}$	$(\gamma_d)_{en}$	$(w)_{en}$	$(e)_{en}$	$(S)_{en}$
Unit	[in.]	[-]	[in.]	[g]	[in.]	[g]	[pcf]	[%]	[-]	[%]
			(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)

**Note:**

- 1- Unlike  $(H)_{st}$  and  $(\gamma_d)_{st}$  which are input parameters,  $(H)_{en}$  and  $(\gamma_d)_{en}$  are automatically calculated based on the last step of the test.
- 2- All of the above calculations are performed using soil volume and density relations.



### 4-3 TEST TABLES

Two tables are considered for the test data in the current software. Note that the “Dial trend” parameter refers to the trend of readings as the settlement increases and is automatically detected by the software.

#### 4-3-1 WHOLE TEST

This table is related to the summary of consolidation test and each row represents the end of a loading step. In the upcoming equations the index "st" corresponds to the start of the test. Indices "m" and "n" also correspond to the "m<sup>th</sup>" and the "n<sup>th</sup>" step of the test where "n = m + 1".

Table 4-2 – Parameters used in the “Whole Test” table

Description	Step	Vertical stress	Apparatus calibration	Dial reading	Corrected dial reading	Height change	Height	Axial strain	Void ratio	Coefficient of volume (re)compressibility	Constrained (re)compression modulus of elasticity
Parameter	Step	P	$\Delta_a$	d	$d_c$	$\Delta H$	H	$\varepsilon$	e	$m_v/m_{vr}$	$E'_c/E'_{cr}$
Unit	[–]	[ksf]	[in.]	[–]	[–]	[in.]	[in.]	[%]	[–]	[1/ksf]	[ksf]
					(*)	(*)	(*)	(*)	(*)	(*)	(*)

Calculations are as below:

$$\text{if Dial trend: Increase} \Rightarrow \begin{cases} (d_c)_n = (d)_n - (\Delta_a)_n \\ (\Delta H)_n = (d_c)_n - (d_c)_{st} \end{cases}$$

$$\text{if Dial trend: Decrease} \Rightarrow \begin{cases} (d_c)_n = (d)_n + (\Delta_a)_n \\ (\Delta H)_n = (d_c)_{st} - (d_c)_n \end{cases}$$

$$(H)_n = (H)_{st} - (\Delta H)_n$$

$$(\varepsilon)_n = \frac{(\Delta H)_n}{(H)_{st}}$$

$$(e)_n = (e)_{st} - (\varepsilon)_n [1 + (e)_{st}]$$

$$(m_v)_n \text{ or } (m_{vr})_n = \frac{(\varepsilon)_n - (\varepsilon)_m}{(P)_n - (P)_m} \quad \text{depends on the loading history \& direction}$$

$$(E'_c)_n \text{ or } (E'_{cr})_n = \frac{1}{(m_v)_n \text{ or } (m_{vr})_n} \quad \text{depends on the loading history \& direction}$$

**Note:** In the current software, whenever at least a portion of the applied stress is previously experienced by the soil sample, parameters  $m_v$  and  $E'_c$  are substituted with  $m_{vr}$  and  $E'_{cr}$ .

#### 4-3-2 LOADING STEPS

This table is related to each of the loading steps and as can be seen, by the use of indices, each of the parameters is dedicated to a specific time or consolidation degree.

Table 4-3 – Parameters regarding each of the “Loading Steps”

Description	Elapsed time	Dial reading	Corrected dial reading	Height change in each step	Height change	Height	Axial strain	Void ratio
Parameter	$t$	$d$	$d_c$	$\Delta h$	$\Delta H$	$H$	$\varepsilon$	$e$
Start of step	$t_i = 0$	$d_i$	$d_{ic}$	$\Delta h_i$	$\Delta H_i$	$H_i$	$\varepsilon_i$	$e_i$
... [%] of primary consolidation	0	$d_0$	$d_{0c}$	$\Delta h_0$	$\Delta H_0$	$H_0$	$\varepsilon_0$	$e_0$
	50	$d_{50}$	$d_{50c}$	$\Delta h_{50}$	$\Delta H_{50}$	$H_{50}$	$\varepsilon_{50}$	$e_{50}$
	90	$d_{90}$	$d_{90c}$	$\Delta h_{90}$	$\Delta H_{90}$	$H_{90}$	$\varepsilon_{90}$	$e_{90}$
	100	$t_{100}$	$d_{100}$	$d_{100c}$	$\Delta h_{100}$	$\Delta H_{100}$	$H_{100}$	$\varepsilon_{100}$
End of step	$t_f$	$d_f$	$d_{fc}$	$\Delta h_f$	$\Delta H_f$	$H_f$	$\varepsilon_f$	$e_f$
Unit	[min]	[–]	[–] (* )	[in.] (* )	[in.] (* )	[in.] (* )	[%] (* )	[–] (* )

Calculations regarding the " $n^{th}$ " hypothetical step are as follows:

$$\text{if Dial trend: Increase} \Rightarrow \begin{cases} d_c = d - (\Delta_a)_n \\ \Delta h = d_c - d_{ic} \\ \Delta H = d_c - (d_c)_{st} \end{cases}$$

$$\text{if Dial trend: Decrease} \Rightarrow \begin{cases} d_c = d + (\Delta_a)_n \\ \Delta h = d_{ic} - d_c \\ \Delta H = (d_c)_{st} - d_c \end{cases}$$

$$H = (H)_{st} - \Delta H$$

$$\varepsilon = \frac{\Delta H}{(H)_{st}}$$

$$e = (e)_{st} - \varepsilon[1 + (e)_{st}]$$

## 4-4 RESULTS ANALYSIS

### 4-4-1 WHOLE TEST

In the current software, after clicking on the “Solve” button, the “Casagrande” and the “Simplified” methods will be accessible in order to evaluate the parameters below:

- (\*)  $P'_c$ : Effective preconsolidation stress, [ksf].
- (\*)  $C_c$ : Compression index, [-].
- (\*)  $C_s$ : Swelling index, [-].

Each of the mentioned methods is fully described along with corresponding tools and options in the software. Separate options are also dedicated to altering the view status of the construction lines and deleting solve data.

#### 4-4-1-1 CASAGRANDE METHOD

##### 4-4-1-1-1 THEORY

###### ❖ $P'_c$

A- " $e - \log(P)$ " graph.

B- Point of maximum curvature on the initial part of the curve.

C- Tangent line to the curve at "B".

D- Horizontal line through "B".

E- Line bisecting angle made by lines "C" and "D".

F- Tangent to steepest linear portion of data curve.

G- Intersection point of lines "E" and "F" is the effective preconsolidation stress.

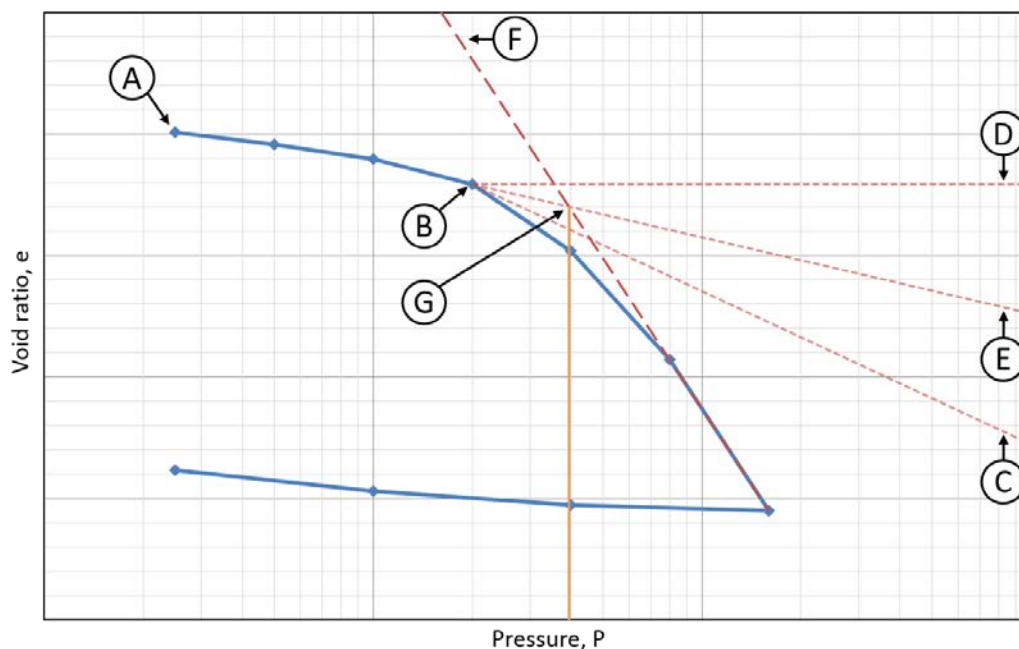


Figure 4-1 – Determination of effective preconsolidation stress using Casagrande method

###### ❖ $C_c$

The absolute slope of the "F" line (in the Casagrande method) is  $C_c$ .

###### ❖ $C_s$

Determination of this parameter depends on the engineering judgment to some extent and is affected by the slope of " $e - \log(P)$ " graph wherever the stress value is equal to or less than the effective preconsolidation stress. The absolute value of the selected sections' average slope equals  $C_s$ .

#### 4-4-1-1-2 APPLICATION

##### ❖ $\underline{C}_s$

This parameter is affected by the slope of " $e - \log(P)$ " graph in the following sections:

- Initial: The options "Mode 1-4", consider the slope of the best linear fit among the first 2-5 points of the graph.
- Unloading steps
- Reloading steps

The  $C_s$  line is drawn from the first point with the average slope of the chosen options above. This line is an initial guess and can be altered according to the user's will and engineering judgment.

##### ❖ $\underline{C}_c$

Drawing the  $C_c$  line is somehow equal to step "F" in section 4-4-1-1-1 and is according to one of the following criteria:

- Steepest line: The line with the maximum (absolute) slope in the " $e - \log(P)$ " graph. This option is recommended by ASTM D2435.
- Modes 1 to 4: The line starts from the last loading step and depending on the choice, "Mode 1-4", its slope equals the slope of the best linear fit among the last 2-5 loading steps.

This line is also considered as an initial guess and can be altered by the user's will.

##### ❖ $\underline{P}'_e$

The point of maximum curvature in the initial part of the curve (equal to step "B" in section 4-4-1-1-1) is chosen and the remaining steps for the determination of  $P'_e$  will automatically be performed.

4-4-1-2 SIMPLIFIED METHOD

 4-4-1-2-1 THEORY

 ❖  $P'_c$ 

 A- " $e - \log(P)$ " graph.

B- Straight portion of the initial recompression curve.

C- Backward projection of the normal consolidation line.

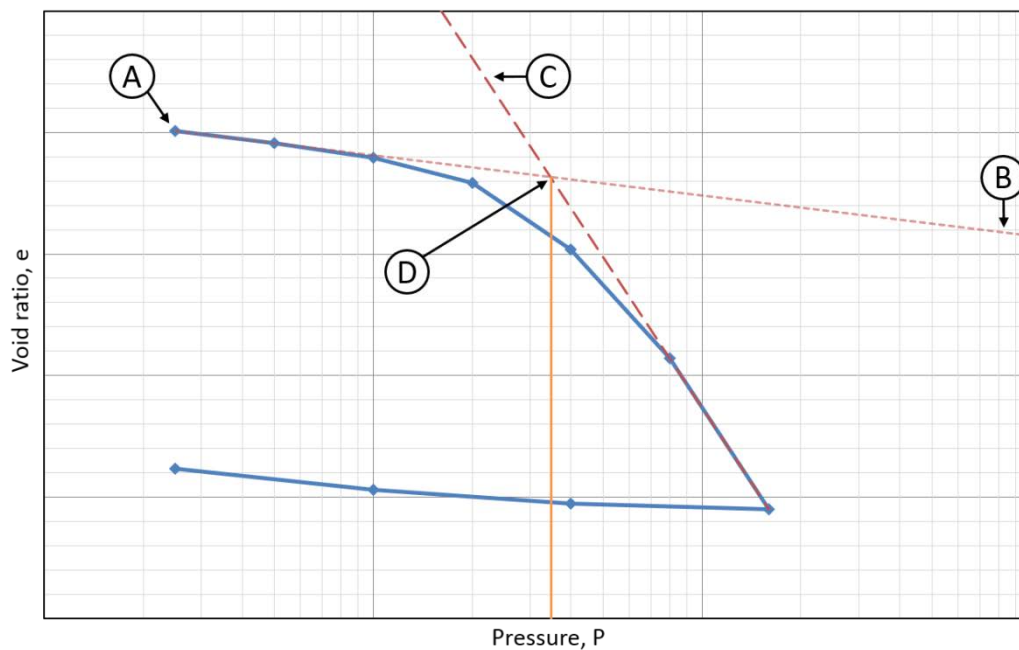
 D- Horizontal coordinate of the intersection point of lines "B" and "C" is  $P'_c$ .


Figure 4-2 – Determination of effective preconsolidation stress using Simplified method

 ❖  $C_c$ 

 The absolute slope of the "C" line (in the Simplified method) is  $C_c$ .

 ❖  $C_s$ 

 The absolute slope of the "B" line (in the Simplified method) is  $C_s$ .

#### 4-4-1-2-2 APPLICATION

##### ❖ $C_s$

Drawing the  $C_s$  line is equal to step "B" in section 4-4-1-2-1 and is affected by the slope of " $e - \log(P)$ " graph in the following sections:

- Initial: The options "Mode 1-4", consider the slope of the best linear fit among the first 2-5 points of the graph.
- Unloading steps
- Reloading steps

The  $C_s$  line is drawn from the first point with the average slope of the chosen options above. This line is an initial guess and can be altered according to the user's will and engineering judgment.

##### ❖ $C_c$

Drawing the  $C_c$  line is equal to step "C" in section 4-4-1-2-1 and is according to one of the following criteria:

- Steepest line: The line with the maximum (absolute) slope in the " $e - \log(P)$ " graph.
- Modes 1 to 4: The line starts from the last loading step and depending on the choice, "Mode 1-4", its slope equals the slope of the best linear fit among the last 2-5 loading steps.

This line is also considered as an initial guess and can be altered by the user's will.

##### ❖ $P'_c$

According to Step "D" in section 4-4-1-2-1, the horizontal coordinate of the intersection point of lines  $C_s$  and  $C_c$  is automatically defined and reported as  $P'_c$ .

#### 4-4-2 LOADING STEPS

In the current software, after clicking on the “Solve” button, the “logarithm” and the “square root of time” methods will be accessible in order to analyze the loading steps where dial-time readings are available. The resulting parameters are as below:

- (\*)  $H_{dr}$ : Length of the drainage path at 50 [%] consolidation, [in.].
- (\*)  $C_v$ : Coefficient of consolidation, [ $\text{in.}^2/\text{min}$ ].
- (\*)  $C_\alpha$ : Secondary compression index, [-].
- (\*)  $r_i$ : Percentage of elastic settlement, [%].
- (\*)  $r_p$ : Percentage of primary consolidation settlement, [%].
- (\*)  $r_s$ : Percentage of secondary consolidation settlement, [%].

Each of the mentioned methods is fully described along with corresponding tools and options in the software. Separate options are also dedicated to altering the view status of the construction lines and deleting solve data.

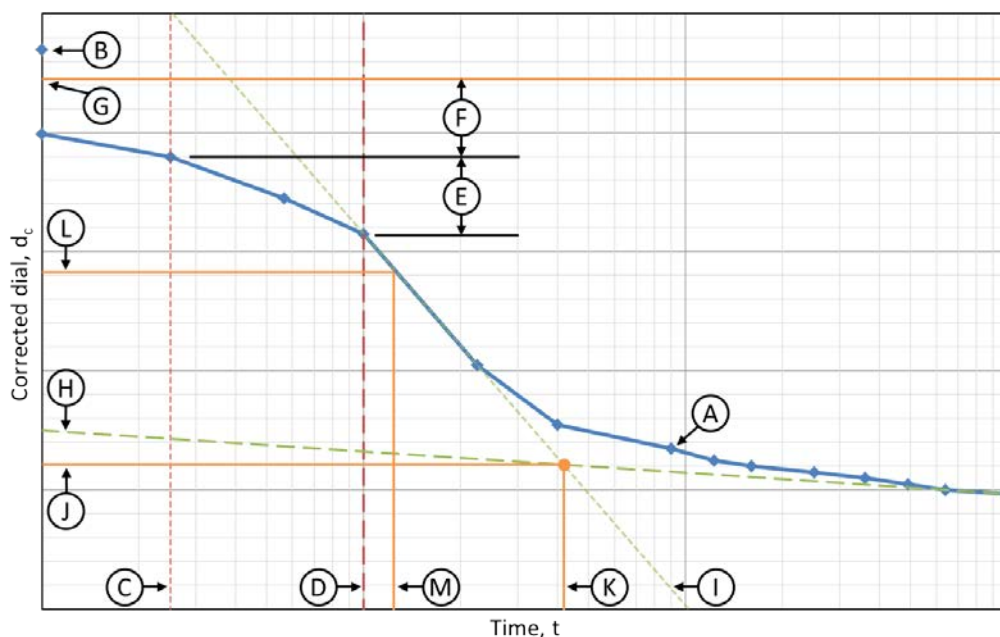


4-4-2-1 LOGARITHM OF TIME METHOD

 4-4-2-1-1 THEORY

 ❖  $d_{0c}$  &  $d_{100c}$ 

- A- " $d_c - \log(t)$ " graph.
- B- Corrected dial at  $t = 0$  ( $d_{ic}$ ).
- C- Vertical line  $t = t_a$  selected for the interpretation of 0 [%] consolidation.
- D- Second vertical line  $t = t_b = 4t_a$  for the interpretation of 0 [%] consolidation. Note that the axial strain corresponding to  $t = t_b$  has to be greater than  $\frac{1}{4}$  and less than  $\frac{1}{2}$  of the total axial strain of the loading step.
- E- Increment of corrected dial between  $t_a$  and  $t_b$ .
- F- Increment of corrected dial equal to "E".
- G- Intersection point of line "F" and the vertical axis is  $d_{0c}$ .
- H- Linear fit of the ending portion of curve "A".
- I- Linear fit of the steepest portion of curve "A".
- J- Corrected dial corresponding to the intersection point of lines "H" and "I" is  $d_{100c}$ .
- K- Time corresponding to the intersection point of lines "H" and "I" is  $t_{100}$ .
- L-  $d_{50c}$  is the average of  $d_{0c}$  and  $d_{100c}$ .
- M- Time corresponding to  $d_{50c}$  according to curve "A" is  $t_{50}$ .


 Figure 4-3 – Determination of  $d_{0c}$  and  $d_{100c}$  using logarithm of time method

**Note:** The method described within ASTM D2435 for the determination of  $d_{0c}$  (steps "C" to "G") is one instance of the following general approach:

- 1-  $t = t_a$  and  $t = t_b$  have to be chosen in such a way that  $t_b > t_a$  and the axial strain corresponding to both  $t_a$  and  $t_b$  are less than 60 [%] of the total axial strain of the loading step. Note that  $\frac{t_b}{t_a}$  does not necessarily have to be equal to 4.
- 2-  $d_{0c}$  is calculated as:

$$d_{0c} = \frac{d_a \sqrt{t_b} - d_b \sqrt{t_a}}{\sqrt{t_b} - \sqrt{t_a}}$$

where  $d_a$  and  $d_b$  are corrected dials corresponding to  $t_a$  and  $t_b$ , respectively.

❖  $H_{dr}, C_v, C_\alpha, r_i, r_p$  &  $r_s$

Final calculations are as below:

$$H_{dr} = \begin{cases} 0.5H_{50} & \text{Double drainage} \\ H_{50} & \text{Single drainage} \end{cases}$$

$$C_v = \frac{0.197H_{dr}}{t_{50}}$$

$$C_\alpha = -\text{Slope}(e, \log(t)) \quad t \geq t_{100}$$

$$r_i = \frac{d_{ic} - d_{0c}}{d_{ic} - d_{fc}}$$

$$r_p = \frac{d_{0c} - d_{100c}}{d_{ic} - d_{fc}}$$

$$r_s = \frac{d_{100c} - d_{fc}}{d_{ic} - d_{fc}}$$

**Note:**

- 1- The general equation for the determination of  $C_v$  is:

$$C_v = \left( \frac{T_v H_{dr}}{t} \right)_U$$

where:

$U$ : Degree of consolidation, [%].

$H_{dr}$  (\*): Length of the drainage path at 50 [%] consolidation, [mm]. This parameter is constant during each loading step.

$T_v$  (\*): Time factor corresponding to the specified degree of consolidation. It is calculated as follows:

$$T_v(U) = \begin{cases} \frac{\pi}{4} \left( \frac{U}{100} \right)^2 & U < 60[\%] \\ -0.085 - 0.933 \log \left( 1 - \frac{U}{100} \right) & U \geq 60[\%] \end{cases}$$

$t$  (\*): Time corresponding to the specified degree of consolidation, [min]. It can be derived either using the graph or linear interpolation.

According to the above description, it is recommended to use  $U = 50$  [%] in ASTM D2435 and therefore, the equation is presented as  $C_v = \frac{0.197H_{dr}}{t_{50}}$ .

- 2- In the current software, various values of  $U$  within the range of (0,100) can be used for the analysis and calculation of  $C_v$ . Other parameters can be evaluated accordingly.
- 3- Using the "View  $U$  variations ..." tool, the user can investigate the variations of  $C_v$  for  $U \in (0,100)$ . As a result  $C_v$  can be determined in such a way that leads to minimum error.

- 4-  $C_\alpha$  is calculated as the negative of the best linear trendline's slope passing through  $(t_{100}, e_{100})$  and the afterwards points in the " $e - \log(t)$ " graph. As a result,  $C_\alpha$  is positive and negative in loading and unloading steps, respectively.

#### 4-4-2-1-2 APPLICATION

##### ❖ $d_{0c}$

This section somehow equals steps "B – G" in section 4-4-2-1-1 and includes the following options:

- Initial dial: By using this option,  $d_{0c}$  is considered equal to  $d_{ic}$  and therefore  $r_i = 0$  [%].
- Standard: This option automatically applies the specified method in ASTM D2435. Note that the  $t = t_a$  line can be moved by the user.
- General: corresponds to the general approach where the user can move both lines  $t = t_a$  and  $t = t_b$ .

##### ❖ $d_{100c}$ & $t_{100}$

This section equals steps "H – K" in section 4-4-2-1-1 and includes the following options:

- Steepest line: The line with the maximum slope in the " $d_c - \log(t)$ " graph is automatically chosen and illustrated.
- End line: corresponds to the final part of the " $d_c - \log(t)$ " graph. This line is started from the last point and its slope varies depending on the choice. "Modes 1-4" represent the slope of the best linear fit among the last 2-5 points of the graph.

The junction point of "Steepest line" and "End line" represent the end of primary consolidation; therefore the horizontal and vertical coordinates of the junction point would be  $t_{100}$  and  $d_{100c}$ , respectively. Note that both "Steepest line" and "End line" can be altered by the user's will and engineering judgment.

##### ❖ U

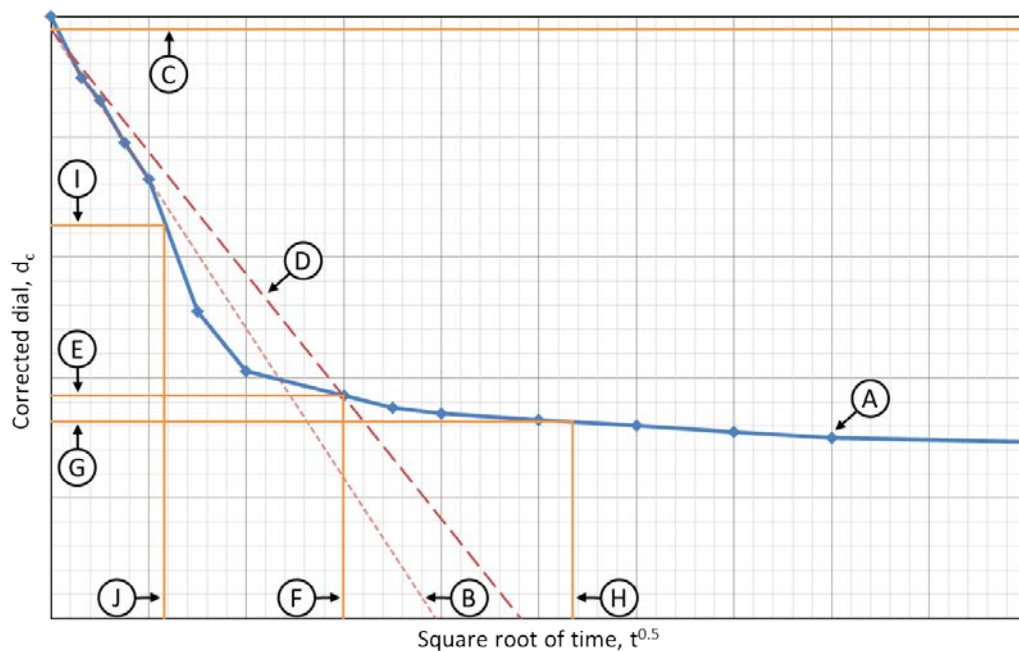
The value of "U" corresponding to the solution is determined by the user and other parameters are calculated accordingly.

4-4-2-2 SQUARE ROOT OF TIME METHOD

 4-4-2-2-1 THEORY

 ❖  $d_{0c}$  &  $d_{100c}$ 

- A- " $d_c - \text{sqrt}(t)$ " graph.
- B- Straight line fit through early time data.
- C- Extension of line "B" to axis  $t = 0$ . The junction point corresponds to  $d_{0c}$ .
- D- Construction line with slope =  $\frac{1}{1.15}$  times that of line "B".
- E- Corrected dial at the intersection of line "D" and graph "A" is  $d_{90c}$ .
- F- Time at the intersection of line "D" and graph "A" is  $t_{90}$ .
- G-  $d_{100c}$  is  $\frac{1}{9}$  more than the difference between  $d_{0c}$  and  $d_{90c}$  (Lines "C" and "E").
- H-  $t_{100}$  equals the time correspondent to  $d_{100c}$ .
- I-  $d_{50c}$  is the average of  $d_{0c}$  and  $d_{100c}$ .
- J-  $t_{50}$  equals the time correspondent to  $d_{50c}$ .


 Figure 4-4 – Determination of  $d_{0c}$  and  $d_{100c}$  using square root of time method

**Note:** The method described within ASTM D2435 for the determination of  $d_{100c}$  (steps "D – G") is one instance of the following general approach:

- 1- The  $U$  parameter has to be chosen in such a way that  $U \in [60,100)$  and the slope of line "D" is calculated as:

$$Slope_D = \frac{Slope_B}{\alpha(U)}$$

$$\alpha(U) = \frac{2}{\frac{U}{100} \sqrt{\pi}} \sqrt{-0.085 - 0.933 \log \left(1 - \frac{U}{100}\right)}$$

According to the above description, it is recommended to use  $U = 90$  [%] in ASTM D2435, but in the general approach  $U \in [60,100)$ .

- 2- Line "D" is drawn starting from the point  $d_{0c}$  with the calculated slope.
- 3- Intersection point of line "D" and graph "A" is determined.
- 4- Vertical and horizontal coordinates of the intersection point in Step 3 are  $d_{Uc}$  and  $t_U$ , respectively.
- 5-  $d_{100c}$  is calculated as:

$$d_{100c} = \begin{cases} d_{0c} + \frac{1}{U}(d_{Uc} - d_{0c}) & \text{Dial trend: Increase} \\ d_{0c} - \frac{1}{U}(d_{0c} - d_{Uc}) & \text{Dial trend: Decrease} \end{cases}$$

❖  $H_{dr}, C_v, C_\alpha, r_i, r_p$  &  $r_s$

Final calculations are as below:

$$H_{dr} = \begin{cases} 0.5H_{50} & \text{Double drainage} \\ H_{50} & \text{Single drainage} \end{cases}$$

$$C_v = \frac{0.848H_{dr}}{t_{90}}$$

$$C_\alpha = -\text{Slope}(e, \log(t)) \quad t \geq t_{100}$$

$$r_i = \frac{d_{ic} - d_{0c}}{d_{ic} - d_{fc}}$$

$$r_p = \frac{d_{0c} - d_{100c}}{d_{ic} - d_{fc}}$$

$$r_s = \frac{d_{100c} - d_{fc}}{d_{ic} - d_{fc}}$$

**Note:**

- 1- The general equation for the determination of  $C_v$  is:

$$C_v = \left( \frac{T_v H_{dr}}{t} \right)_U$$

where:

$U$ : Degree of consolidation, [%].

$H_{dr}$  (\*): Length of the drainage path at 50 [%] consolidation, [mm]. This parameter is constant during each loading step.

$T_v$  (\*): Time factor corresponding to the specified degree of consolidation. It is calculated as follows:

$$T_v(U) = \begin{cases} \frac{\pi}{4} \left( \frac{U}{100} \right)^2 & U < 60[\%] \\ -0.085 - 0.933 \log \left( 1 - \frac{U}{100} \right) & U \geq 60[\%] \end{cases}$$

$t$  (\*): Time corresponding to the specified degree of consolidation, [min]. It can be derived either using the graph or linear interpolation.

According to the above description, it is recommended to use  $U = 90$  [%] in ASTM D2435 and therefore, the equation is presented as  $C_v = \frac{0.848H_{dr}}{t_{90}}$ .

- 2- In the current software, various values of  $U$  within the range of [60,100) can be used for the analysis and calculation of  $C_v$ . Other parameters can be evaluated accordingly.
- 3- Using the "View  $U$  variations ..." tool, the user can investigate the variations of  $C_v$  for  $U \in [60,100)$ . As a result  $C_v$  can be determined in such a way that leads to minimum error.

4-  $C_\alpha$  is calculated as in “logarithm of time” method (section 4-4-2-1-1).

#### 4-4-2-2-2 APPLICATION

##### ❖ $d_{oc}$

This section equals steps "B" and "C" in section 4-4-2-2-1. Using each of the options “Mode 1-4”, the best linear fit among the second point and 1-4 afterward points, is drawn and extended to the  $t = 0$  axis. Same as previous methods, this line is considered as an initial guess and can easily be altered and moved by the user’s will.

##### ❖ $d_{100c}$ & $t_{100}$

These parameters are automatically calculated after the determination of  $U$ .

##### ❖ $U$

The value of " $U$ " corresponding to the solution is determined by the user and other parameters such as  $d_{100c}$  and  $t_{100}$ , are calculated accordingly.



## 5 CONTACT US

Feel free to contact us regarding any criticism, recommendation or additional information.

- 1- Visit [www.soiloffice.com/ContactUs](http://www.soiloffice.com/ContactUs)
- 2- Send an e-mail to [info@soiloffice.com](mailto:info@soiloffice.com)
- 3- Call (+98) 912 313 4107 – Emad Zargaran.  
(Also available on WhatsApp and LINE)
- 4- Call “Emad.Zargaran” via Skype.

## 6 LIST OF SYMBOLS

Symbol	Description
$(*)_{en}$	<i>each of the parameters at the end of the test</i>
$(*)_m$	<i>each of the parameters in the “m<sup>th</sup>” step of the test</i>
$(*)_n$	<i>each of the parameters in the “n<sup>th</sup>” step of the test</i>
$(*)_{st}$	<i>each of the parameters at the start of the test</i>
$*_f$	<i>each of the parameters at the end of each step</i>
$*_i$	<i>each of the parameters at the start of each step</i>
$*_{number}$	<i>each of the parameters at the specified percentage of the primary consolidation of each step</i>
$C_c$	<i>compression index</i>
$C_s$	<i>swelling index</i>
$C_v$	<i>coefficient of consolidation</i>
$C_\alpha$	<i>secondary compression index</i>
$d$	<i>dial reading</i>
$d_c$	<i>corrected dial reading</i>
$D$	<i>sample diameter</i>
$e$	<i>void ratio</i>
$E'_c/E'_{cr}$	<i>Constrained (re)compression modulus of elasticity</i>
$Elev.$	<i>ground elevation at top of boring</i>
$g_d/\gamma_d$	<i>dry unit weight</i>
$G_s$	<i>specific gravity of soil solids</i>
$GWT$	<i>depth to water table measured from boring top (Ground Water Table)</i>
$H$	<i>sample height</i>
$H_{dr}$	<i>length of the drainage path at 50 [%] consolidation</i>
$H_s$	<i>equivalent height of soil solids</i>
$m_v/m_{vr}$	<i>coefficient of volume (re)compressibility</i>
$M_s$	<i>weight of soil solids</i>
$M_T$	<i>sample moist mass</i>
$P$	<i>vertical stress</i>
$P'_c$	<i>effective preconsolidation stress</i>
$r_i$	<i>percentage of elastic settlement</i>
$r_p$	<i>percentage of primary consolidation settlement</i>
$r_s$	<i>percentage of secondary consolidation settlement</i>
$S$	<i>degree of saturation</i>
$t$	<i>elapsed time</i>
$T_v$	<i>time factor in consolidation</i>
$U$	<i>degree of consolidation</i>
$USCS$	<i>Unified Soil Classification System</i>
$w$	<i>moisture content</i>
$\Delta_a$	<i>apparatus calibration</i>
$\Delta h$	<i>sample height change in each step</i>
$\Delta H$	<i>sample height change</i>
$\varepsilon$	<i>vertical strain</i>