Automatic detection of secondary consolidation in computer controlled oedometer tests

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ABSTRACT: Oedometer tests are one of the most widely used methods to evaluate consolidation behaviour in soils. Reliable, fully automated testing using currently available computer controlled equipment has been hindered by the inherent variability of soils, a function of their nature and geotechnical context. Using Analysis of Variance statistical models, applied to consecutive data clusters of deformation and time for a single vertical load increment, a method was developed which allows virtual shape quantification of a typical log time-deformation plot for individual load increments during an oedometer test. This was achieved by testing the variability of deformation in relation to the variability of time within consecutive data clusters using the F-Test, and establishing the relation between its value and the rate of consolidation for a load increment. It was concluded that at the end of primary consolidation there was a sudden decrease in the values returned by the F-Test, following by stabilization at a lower value during secondary consolidation. This behaviour constitutes an objective indicator for the onset of secondary consolidation during oedometer testing, independent of the soil being tested, which can be used within an algorithm to automate the transition between two consecutive loading increments.

KEYWORDS: Oedometer, consolidation, computer controlled, automated testing, testing software, ANOVA.

1. INTRODUCTION
Recent years have brought us a wide range of testing apparatuses which allow computer control of test procedures, providing users with decreased operation complexity and increased reliability. Automated one-dimensional consolidation systems do away with the need for bulky weights, replacing them with pneumatic or motorized systems for the application of vertical load during a test. However, despite their name, full automation of incremental loading and unloading for a complete oedometer test is still difficult to achieve in a reliable way. Testing specimens of different soil types and geotechnical engineering requires variability in consolidation behaviour, which in turn means that the same automation trigger may not be applicable for different specimens.

Standardised oedometer test methodology requires the incremental application of a vertical load on a laterally confined specimen. To be able to determine the coefficient of consolidation for each load increment, time-deformation readings will be recorded for that increment, plotted to a square root or logarithmic scale and analysed using a curve fitting method (Craig and Knappett 2012). Automation of the transition between loading increments requires the identification of a conditional state indicative of the end point of a load increment. This point can be defined as the time when enough data has been recorded for determination of the coefficient of consolidation. To ensure repeatability and applicability of the automation method, this conditional trigger must not be affected by the variability between test specimens.

2. DEFINITION OF A TRIGGER CONDITION
To avoid dependency between soil properties and trigger conditions, the selected approach focused on statistical analysis of the theoretical data distribution for points defined by time and deformation data. During consolidation of a soil specimen under a given loading increment these parameters will vary in magnitude according to the characteristics of the soil being tested, but they will keep the same type of data distribution expressed by the theoretical curves for oedometer consolidation.

Discrete specimen behaviour during consolidation (initial compression, primary and secondary consolidation) can be related to intervals within the time-deformation data distribution. Standardised test methods rely on this relation for the determination of the coefficient of consolidation (BS1377-Part 5, 1990 and ASTM D2435, 2011) by means of the curve fitting methods. When a specimen fully enters secondary consolidation after application of a vertical load increment during standardised oedometer testing, enough registered data will be available for the application of at least one of the curve fitting methods. Thus it was considered the onset of secondary consolidation would constitute a reliable condition to trigger the transition for the next loading stage.

2.1 Graphical definition of secondary consolidation
Casagrande’s curve obtained by plotting deformation data against time in minutes on a logarithmic scale (Casagrande, 1936) was used to identify secondary consolidation during incremental loading oedometer trial tests performed on remoulded clay. This theoretical curve was chosen because it typically requires a longer increment duration than Taylor’s root of time curve, providing a larger data set for the same data acquisition frequency (Ablowitz 2007).

2.2 Adaptation of theoretical one-dimensional consolidation behaviour for software development
Curve fitting methods are practical and easy to use. However, the design of an algorithm capable of performing the conceptual shape analysis associated with these methods, which comes naturally during direct human interaction, can be very challenging and resource consuming. To circumvent this issue a numerical approach was adopted to virtually quantify the shape of the theoretical consolidation data distribution. This was achieved by splitting test data from the loading increment into consecutive pairs of corresponding clusters of time and deformation data, creating different non-overlapping and statistically comparable populations. The time clusters contained a constant number of consecutive observations with a difference of one second between them.

Each deformation data cluster was compared to its corresponding time data cluster, providing a numerical indicator of consolidation behaviour for that time interval. The analysis of consecutive cluster pairs provides a numerical indicator which can be plotted against time (using the largest time value for each
cluster) on a logarithmic scale, and directly comparable to the shape of the corresponding theoretical consolidation curve. Using this data grouping methodology, Analysis of Variance (ANOVA) statistical models were used to assess the available data.

Linearity analysis was conducted by testing the applicability of a linear regression model through the determination of the coefficient of determination (R²) for each pair of data clusters. The F-Test was also used to test the variability of deformation readings and the respective time readings. Having control of time data means that the result of ANOVA’s F-Test will constitute a good numerical indicator of the variability of deformation data in relation to time.

Figure 1 compares the results of both models with data from a consolidation loading increment on a clay specimen, in which the vertical stress was increased from 400 kPa to 800 kPa.

![Figure 1: Relation between consolidation curve, R² and ANOVA F-test cluster analysis.](image)

The graphical comparison shows a discernible relationship between the behaviour of the statistical indicators and time-deformation data distribution. The same analysis was repeated, with identical results, for different loading increments on different soil specimens. There is an increase of the test parameter value as the consolidation curve approaches linearity during primary consolidation, progressing to an accentuated drop in the statistical test results during the transition between primary and secondary consolidation, and a final stabilisation at a lower value when secondary consolidation is ongoing. Although this behaviour is observed for both indicators, the coefficient of determination shows a milder reaction to changes in the consolidation curve than ANOVA’s F-test, in addition to an increased variability during secondary consolidation.

This association between the onset of secondary consolidation and stabilization of F-Test at a lower value relative to a previously identified maximum constitutes an objective indicator useful for viable software implementation during the automation of the transition between load increments.

2.3 Experimental test results

The F-Test trigger condition was implemented within the software used to control an oedometer system. Tests conducted on clays showed a consistent automated transition between load increments occurring at the start of secondary consolidation. Manual data analysis using the log time method confirmed there was enough data for each stage for accurate determination of the coefficient of standardized consolidation parameters. Additionally, it was observed that the trigger condition was also applicable for unloading stages, as the inverted time-deformation distribution obtained during unloading produced similar results under clustered F-test analysis.

Further data obtained from automated increment transition tests showed a decrease in total test time without loss of relevant data. Testing is still being conducted to quantify this decrease in duration. It will be difficult to reach a specific value as the beginning of secondary consolidation will change according to specimen characteristics. However, at an early stage of testing, results obtained showed an average duration decrease of 42% in relation to the 24 hour increments suggested by BS 1377 part 5 1990. Given its nature, the ANOVA F-test trigger should activate on the onset of secondary consolidation, even for specimens requiring longer consolidation times (i.e., above 24 hours), unless a user defined duration limit is established.

3 CONCLUSION

To automate computer controlled oedometer tests, the onset of secondary consolidation was selected as the condition triggering the transition between vertical load increments.

A study of time-deformation data relying on variance analysis and linearity tests was used to identify an indicator of secondary consolidation, independent of the characteristics of the specimen being tested. The coefficient of determination R² and ANOVA’s F-Test were used to quantify the linearity and variance, respectively, of the test data. It was observed that, independent of the specimen being tested, statistical test values decreased at the end of primary consolidation, stabilising at lower values during secondary consolidation. The F-Test provided better results than R² after primary consolidation. Its behaviour was then used as a conditional trigger in test control software, successfully automating transitions between both loading and unloading increments during oedometer testing, resulting in an average decrease of 42% in test duration.

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