Application and comparison of multistage triaxial compression test procedures on reconstituted Ankara clay

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ABSTRACT

The ability to conduct conventional triaxial compression tests on multiple identical specimens is restricted by available sample quantity, sample homogeneity, as well as testing duration. Multistage triaxial testing is an alternative method to tackle these issues by using a single specimen sheared under different confining stresses to attain the strength parameters. Although there are widely accepted procedures to decide when to stop each shearing stage and proceed to the next stress level, the applicability of these procedures on different soil types is still a question. This study examines the applicability of combinations of two multistage triaxial testing procedures (Rational Procedure and Minimum Slope) under two different deviator stress conditions (Sustained or Cyclic) during confining stress increase. The outcome is compared to conventional triaxial test results for undrained and drained shearing of reconstituted specimens of high-plasticity Ankara Clay. Out of the four options, the rational procedure with cyclic deviator loading and minimum slope with cyclic deviatoric loading conditions, are found to give the most accurate strength parameters in reference to single-stage test results. The maximum number of the shearing-reconsolidation sequences applicable before strength loss is also investigated for each multistage triaxial testing procedure.

Keywords: multistage triaxial test; high plasticity clays; Ankara clay; strength parameters.

1. Introduction

In almost all geotechnical projects, the geosystem design depends on the soil strength parameters. The conventional triaxial test is the most widely used experiment to attain soil strength and deformation characteristics reliably (Budhu 2015, Choi et al. 2018, Reis Ferreira et al. 2016). In triaxial test, at least three identical specimens are consolidated under different confining stresses and sheared to draw the failure envelope and investigate the strength parameters. In order to address the issues associated with sample scarcity, heterogeneity errors, prolonged duration and high cost of tests, the multistage triaxial test is developed as a feasible alternative. In the multistage triaxial test, possibly introduced by De Beer (1950) for the first time, one specimen is consolidated under certain effective stress and sheared until a close-to-failure point (Head 1982). Then, the specimen is sheared again following reconsolidation under a higher effective confining pressure. This sequence is repeated at least three times to determine the failure envelope and strength parameters. Many researchers have studied the viability of a multistage triaxial test for assessment of strength parameters on different soil and rock types (Alyousif 2015, Banerjee et al. 2020, Gräsle 2011, Khosravi et al. 2012, Kim and Ko 1979 , Mishra and Verma 2015 , Shahin and Cargeeg 2011, Soranzo 1988, Vergara et al. 2015, Wild et al. 2017). Consequently, various approaches are recommended to determine the shearing termination point that is the key factor in conducting a multistage triaxial test (Alyousif 2015, Ho and Fredlund 1987, Nambiar et al. 1985 , Saeedy and Mollah 1988). Each shearing stage should be stopped where the peak strength of the soil can be measured or estimated but at the same time prevent any further axial strain to mobilize the friction angle and create a distinct failure plane in the specimen.

Kenny and Watson (1961) suggest that the multistage triaxial test is best applicable in undrained tests. It can be applied to drained tests for clays with very low sensitivity. Also, they assert that clay specimens with low sensitivity can withstand three sequences of shearing-reconsolidation without considerable strength reduction.

Nambiar et al. (1985) propose the rational procedure. Following the rational procedure, the specimen is sheared at each sequence until 2-4% axial strain and reconsolidated under a higher effective confining stress. At each sequence, the stress and pore water pressure at failure is estimated using the proposed method by Kondner (1963). This approach gives accurate strength parameters for undrained tests. However, it is not applicable to drained tests, where the specimen volume is not preserved, and pore pressure is constant. They also suggested doubling the effective confining pressure at each sequence to minimize the previous shearing effect on the specimen and better recovery.

Table 1. Ankara clay properties from different studies

	Clay content (%)	**LL (%)**	**PI**	**G_s**	**Classification**
Erguler & Ulusoy (2003)	11 - 75	44 - 103	17 - 67	2.60	-
Avsar et al. (2005)	66 - 67	51 - 93	24 - 51	-	CH and MH
Avsar et al. (2009)	39 - 60	75 - 112	42 - 75	-	CH
Cokca & Tilgen (2010)	67.9	48	27	2.73	CL
Binal et al. (2016)	36	88.7	53.7	-	CH
Akgun et al. (2017)	61.5 – 65.6	52 – 62.9	34.8 – 38.2	2.6 – 2.8	CH
	43.2 – 85	40.2 – 49.3	23.8 – 32.1	2.7 – 2.78	CL
	51.8 – 80.1	47.3 – 81.8	26.3 – 36.7	2.68 – 2.84	MH-CH-CL

Recently, multistage procedures have been applied on drained tests and show promising results (Alyousif 2015, Choi et al. 2018, Hormdee et al. 2012, Kayaturk et al. 2021, Ravi Sharma et al. 2011, Rivera-Hernandez et al. 2021, Taheri et al. 2012).

Alyousif (2015) investigated two new criteria to stop the shearing at each sequence in drained tests on a sand sample, namely Minimum Slope and Maximum Curvature. In the first one, the shearing is stopped, and shearing is finished when the line passing through two data points on the deviatoric stress-axial strain curve has a slope of 5 kPa/% or less. In the case of the second criterion, when the deviatoric stress-axial strain graph has the maximum curvature, immediately before the curvature decreases as the test continues, the shearing stage should be halted. It is found that the minimum slope approach gives results that better agree with the results of the single-stage conventional triaxial tests for the cohesionless material tested in that study.

Ho and Fredlund (1987), carried out multistage triaxial tests on unsaturated soils for the first time. They introduced two deviatoric unloading conditions, "sustained" and "cyclic." In sustained loading, the deviatoric stress is kept on the soil specimen after the shearing stage, and reconsolidation is started. Whereas in cyclic loading, the deviatoric stress is totally removed from the specimen and the reconsolidation begins. They conclude under sustained loading condition, the accumulation of the strain on the specimen leads to strength reduction due to creep. Under cyclic loading condition, however, the soil specimen recovers better and is likely to obtain more realistic strength parameters.

This study aims to investigate the applicability of available shearing termination criteria (the rational procedure and minimum slope) on reconstituted high plasticity Ankara clay soil sample under two deviatoric loading conditions (sustained and cyclic) at the end of each stage. The most accurate approach on high plasticity Ankara clay is investigated regarding shear strength parameters (c' and ϕ') and elastic modulus (E'_{50}) and Skempton's (1954) pore pressure parameter in undrained test (A_f) with the results of single-stage conventional triaxial test. Moreover, the maximum number of shearing-reconsolidation sequences applicable before a significant strength reduction occurs is examined.

2. Experimental study

2.1. Testing material

Ankara clay is the dominant geological formation of Ankara city, the capital of Turkey. Following the available literature, the physical and mechanical properties of soil samples from different locations in Ankara are summarized in Table 1.

In this study, Ankara clay soil sample is obtained from a construction site at the city center of Ankara. The soil sample is comprised of about 93% fine grains (~58% clay sized, ~35% silt sized) (ASTM D6913-17, ASTM D7928-17). Atterberg limits for the soil sample are obtained following ASTM D4318-17 and it is classified as high plasticity clay according to Unified Soil Classification System (USCS: ASTM D2487-17). Particle size distribution and soil properties are provided in Fig. 1 and Table 2, respectively.

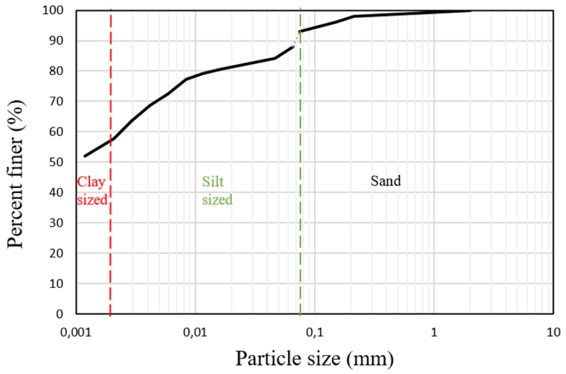

Figure 1. Particle size distribution of Ankara clay sample

Table 2. Ankara clay properties and classification

Property	**Value**
Specific gravity	2.65
Liquid limit (%)	70
Plastic limit (%)	30
PI	40
Clay content (%)	58
Soil activity	0.69
Soil classification	CH

2.2. Testing material preparation

To perform multistage triaxial test on Ankara clay and compare the outcome with single-stage triaxial test results, it is essential to prepare identical soil specimens in dimension, water content, stress history, etc. In this regard, reconstituted specimens are prepared by adding distilled water to the soil sample up to its liquid limit and mixing in a steel container of 30 cm x 30 cm x 20 cm dimensions with a permeable base. The sample is continuously checked by hand to make sure that the slurry was homogenous and free of flocculation of clay particles. Subsequently, a permeable top plate is placed on the box and vertically loaded under 50 kPa by a pneumatic piston connected to an air compressor. The vertical displacement of the top plate is recorded periodically. When the displacement against time becomes asymptotic, the consolidation is stopped, and soil specimens are extracted from the container using thin-walled cutting tubes of the size of triaxial specimen. Dimensions of extracted specimens are measured to be about 35 mm x 80 mm with a negligible deviation. Water content is 50±1 % at random points at top and bottom of the container.

Single and multistage triaxial tests are carried out on identical specimens obtained from the same container consolidated under 50 kPa pressure.

2.3. Experimental setup and program

Fig. 2 shows the manual and fully automated testing setups used for undrained and drained tests respectively.

2.3.1. Single-stage testing program

Four single-stage undrained and four single-stage drained tests were carried out following ASTM D4767-11 , ASTM D7181-20. The specimens were isotropically consolidated under 100 kPa, 200 kPa, 400 kPa and 600 kPa. Nambiar et al. (1985) recommended doubling the effective consolidation stress at each reconsolidation stage for efficient removal of the shearing effect. However, due to the limited capacity of the testing setups available for this study, at the fourth sequence, 600 kPa is employed instead of 800 kPa.

As the first step in all tests, the specimen is saturated by means of back pressure. The Skempton's (1954) B parameter in all single-stage and multistage tests are checked to be higher than 95% to assure that the specimens are saturated. If the B value was lower than 95%, the specimen was held under a higher back pressure for another 24 hours since the saturation of soil is a function of both pressure and time (Lambe and Whitman 1969).

During the consolidation stage, the volume change of the specimen was noted by considering the amount of water draining out of the specimen. Consolidation is assumed to be finished when the volume change in time becomes asymptotic. This was also double-checked by confirming that no volume change in specimen for 24 hours is observed. The consolidation stage was the most time-consuming step due to the low permeability of the Ankara clay specimen. Each specimen was consolidated in at least 48 hours.

Considering consolidation data, using log of time (Casagrande and Fadum 1940) and square root time (Taylor 1948) methods, times for 50% and 90% of consolidation are obtained as 65 minutes and 170 minutes respectively. Following ASTM D2435-04, undrained (CU) and drained (CD) shear rates are set to 0.1 mm/min and 0.005 mm/min respectively. Drained shearing rate was low enough to prevent any excess pore water pressure generation and no excess pore water pressure was observed during the drained tests. Acquired raw data from the single-stage and multistage triaxial tests were corrected for filter paper effect, rubber membrane (Henkel and Gilbert 1952) and parabolic cross-sectional area correction (Toker 2007) following ASTM D4767-11; ASTM D7181-20.

2.3.2. Multistage testing program

Four multistage procedures were implemented, including rational procedure (RP) and minimum slope (MS) approaches, each with sustained (S) and cyclic (C) loading, under undrained and drained conditions.

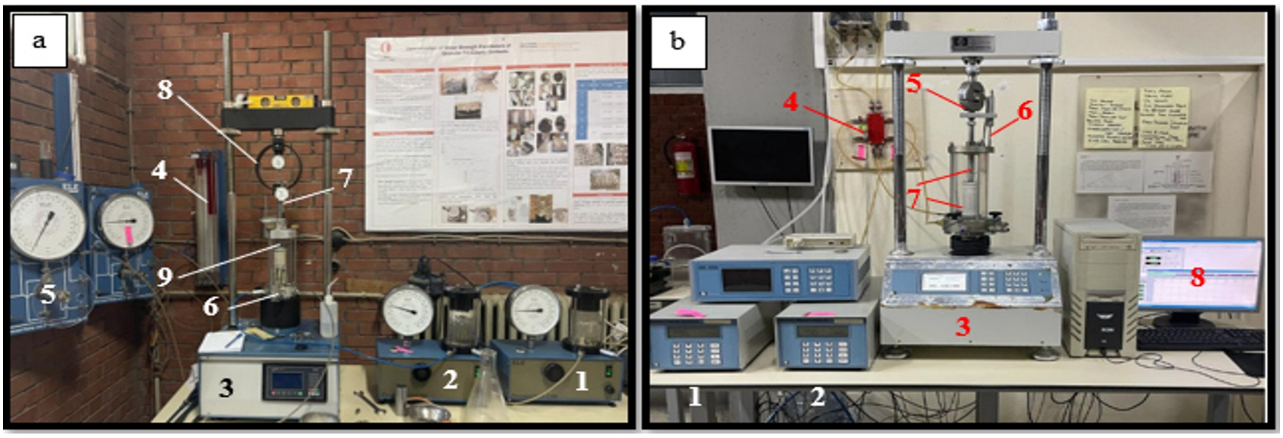

Figure 2. Testing setups a) manual used for CU tests includes: 1) Backpressure control unit, 2) Cell pressure control unit, 3) Load frame and axial motor, 4) Double burette for measuring the drained water volume, 5) Pressure gauge for pore water pressure measurement through the null indicator, 6) Mercury null indicator, 7) Dial gauge for axial deformation measurement, 8) Load cell, 9) Triaxial cell. b) fully automated testing setup used for CD tests is composed of 1) Backpressure Automatic Pressure Controller (APC), 2) Cell pressure Automatic Pressure Controller (APC), 3) Load frame and axial motor, 4) Pore pressure measurement device, 5) Load cell, 6) Axial displacement transducer, 7) Triaxial cell and the loading rod, 8) Controlling interface/software.

The saturation and consolidation stages are similar to the single-stage (SS). During the shearing stage, for the rational procedure (RP), the shearing is halted at about 2% axial strain. Minimum slope (MS) procedure dictates to terminate shearing when the line passing through two data points on deviatoric stress-axial strain curve reaches the slope of 0% or negative values. Shearing termination is followed by deviatoric stress removal in the cyclic loading method. However, in the sustained loading method, the deviatoric stress is kept on the specimen and the specimen is allowed to reconsolidate without removing the axial stress. Ho and Fredlund (1987) claimed that the specimen is better recovered when the stress is removed by maximum speed. Due to the fast unloading, the unloading stress-strain curves could not be recorded and in this study the unloading lines are hypothetical and similar to the initial elastic loading section.

3. Experimental results and discussion

This part presents the results of single-stage and multistage tests both for undrained and drained conditions. During the consolidation of clay specimens, significant volume change is observed. In cyclic loading, the loading frame moved from the specimen and deviatoric stress is removed immediately after shearing phase and at the start of reconsolidation stage. However, in case of the sustained loading, the loading rod is kept on the specimen and after a while due to the deformation of the specimen the deviatoric stress was dropped to zero. Therefore, the shearing phase started by moving the rod to touch the top cap and the deviatoric stress-axial strain curve at each stage starts from the horizontal axis which is similar to cyclic loading case.

3.1. Undrained testing results

3.1.1. Single-Stage vs. Rational procedure

Fig. 3 and 4 present the deviatoric stress-axial strain curves attained from single-stage (SS) and rational procedure under cyclic (RPC) and sustained (RPS) loadings, respectively. First two letters denote test type in the legends of all figures in this section. The numbers show the effective confining pressure under which the specimen is consolidated. The last letter represents the loading condition that is either cyclic or sustained.

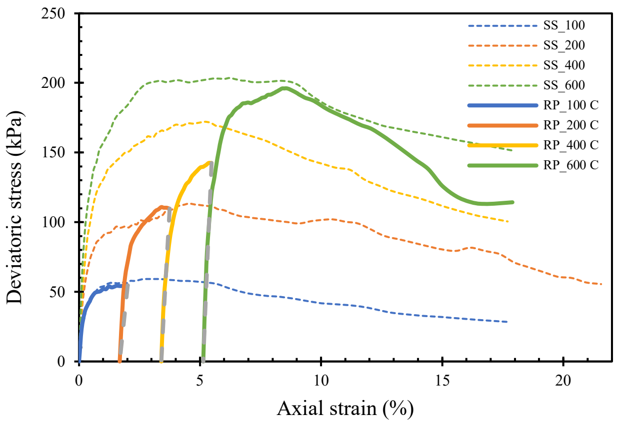

Figure 3. Ankara clay undrained response in Single-Stage vs. Rational Procedure Cyclic

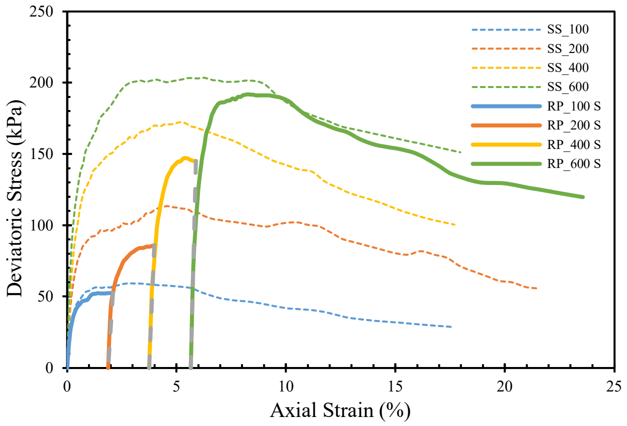

Figure 4. Ankara clay undrained response in Single-Stage vs. Rational Procedure Sustained

The Rational procedure with cyclic loading gives near perfect stress-strain response in the first two sequences, followed by a decrease in peak deviatoric stress at the third sequence. Apparently, the reason for the reduced strength in third sequence is that the experiment stopped at 2% axial strain which is prior to the peak axial strain. However, the data extrapolation could not capture the actual stress and pore water pressure at failure. By extrapolating the results from third sequence it can be observed that the deviatoric stress and pore water pressure are predicted very close to the actual values. The fourth sequence is also acceptable in terms of the peak deviatoric stress. In the rational procedure (RP), since the specimen is loaded at very small strains (about 2%), the disturbance is less compared to minimum slope (MS) procedure and the peak deviatoric stress can be captured even at the fourth sequence. On the other hand, in Rational procedure with sustained loading after first shearing stage the specimen shows a reduction in strength. Although the fourth stage gives a relatively acceptable result in terms of peak deviatoric stress compared to single-stage test, it is observed that the strength parameters found from this procedure are less than the actual values due to the lower strength obtained from second and third stages. The results of RPC and RPS for undrained tests are provided in Table.3.

3.1.2. Single-Stage vs. Minimum slope

In Fig. 5 for Minimum slope with cyclic loading, three sequences of shearing-reconsolidation are presented. Due to a technical issue that happened during the test, the fourth sequence couldn't be recorded. According to Fig. 5 and 6, the MS dictates continuing the shearing until the curve becomes horizontal with a slope of zero. Therefore, the specimen is axially loaded and deformed considerably, leading to strength loss at later sequences. Moreover, the loading condition affects the peak strength value. Due to the creep in sustained loading, the peak deviatoric stress is found to be much lower than the value obtained in cyclic loading. The specimen shows a serious downturn in Figure 6 after the second sequence. This response is also attributed to the sustained loading condition.

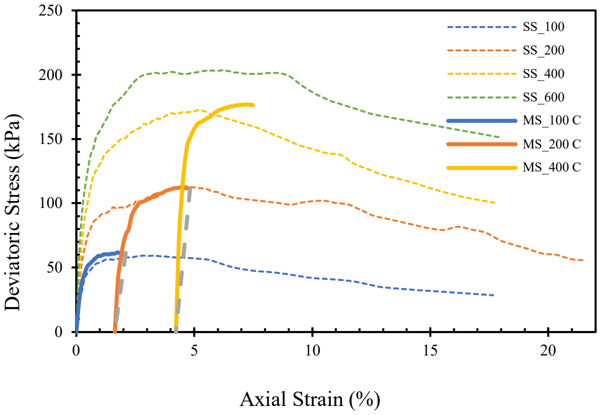

Figure 5. Ankara clay undrained response in Single-Stage vs. Minimum Slope Cyclic

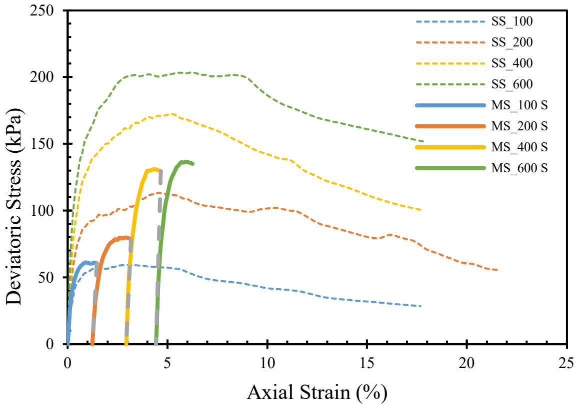

Figure 6. Ankara clay undrained response in Single-Stage vs. Minimum Slope Sustained

3.1.3. Undrained outcome compatibility

The variation of the pore pressure parameter A at failure for single-stage and multistage procedures under cyclic and sustained loading conditions in undrained tests are illustrated in Fig. 7. Pore pressure parameter at failure for single-stage test and RPC is similar. However, MSC and both procedures under sustained loading condition fail to capture the correct excess pore pressure generation regime.

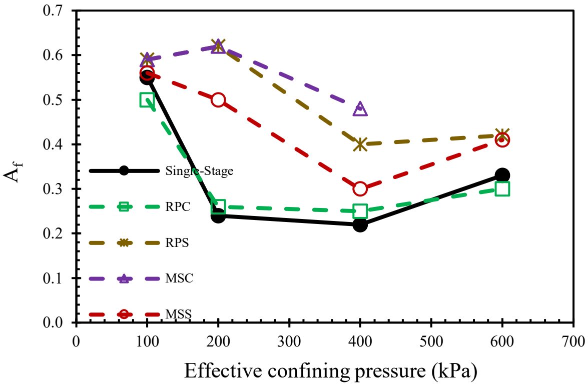

Figure 7. Pore pressure parameter A at failure in single-stage and multistage undrained tests

Secant elastic modulus for single-stage and multistage procedures in undrained tests are provided in Fig. 8. Similar to the pore pressure parameter, the E'_{50} variation by effective confining pressure for RPC matches that of the single-stage tests accurately.

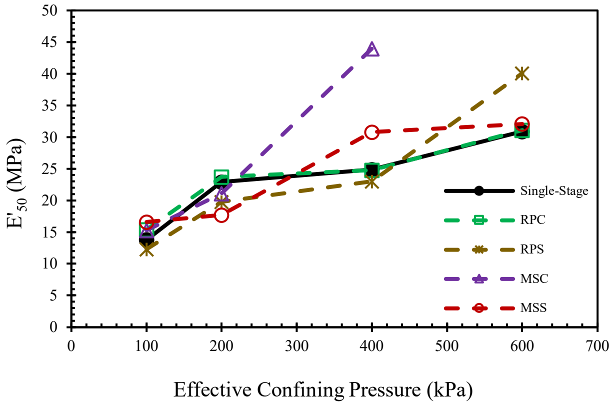

Figure 8. Secant elastic modulus E'_{50} from single-stage and multistage undrained tests

Peak deviatoric stress is considered for the failure of the soil specimen. In order to attain the internal friction angle and soil cohesion, the modified envelopes for single-stage and multistage procedures for undrained tests are illustrated in Fig. 9 and strength parameters are calculated accordingly. Internal friction angle and cohesion of the specimen for single-stage and multistage procedures are provided in Table 3.

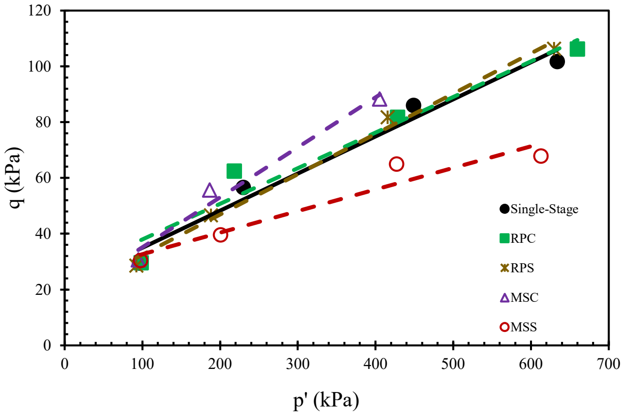

Figure 9. Modified failure envelope for single-stage and multistage undrained tests.

Table 3. Effective strength parameters obtained from single-stage and multistage undrained tests.

Test	**Loading**	**Internal friction angle (◦)**	**Cohesion (kPa)**
Single-stage	-	7.6	22
Rational procedure	Cyclic	7.4	23
Minimum slope		10.3	17.6
Rational procedure	Sustained	8.3	18
Minimum slope		6	19.6

3.2. Drained testing results

3.2.1. Single-Stage vs. Rational procedure

The results of the drained tests for single-stage and RPC and RPS are provided in Fig. 10 and 11. Regarding the first sequence in Fig. 10, since the resolution of load cell used in automatic test setup is 4 kN, at low strains this may cause slight deviation from single-stage curve. However, this is not a major error because in RP we used the data to estimate the failure point using Kondner hyperbolic model. It should be emphasized that all the experiments give almost the same peak deviatoric stress at first sequence. This means that the repeatability of the tests are also justified. Moreover, when the test continues to higher axial strains this error is negligable since 4 kN deviation does not affect the curve considerably at higher stresses near the failure.

The interpretation of the RPC results show that the obtained strength parameters are lower than the actual values. Furthermore, according to Fig. 11, although RPS follows the correct behavior of specimen at first step, in other sequences the deviatoric stress-axial strain relation is not consistent with single-stage test results and this procedure fails to estimate the peak deviatoric stress at later sequences.

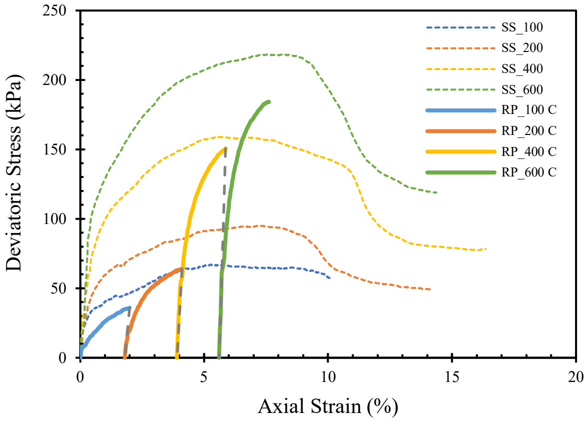

Figure 10. Ankara clay drained response in Single-Stage vs. Rational Procedure Cyclic

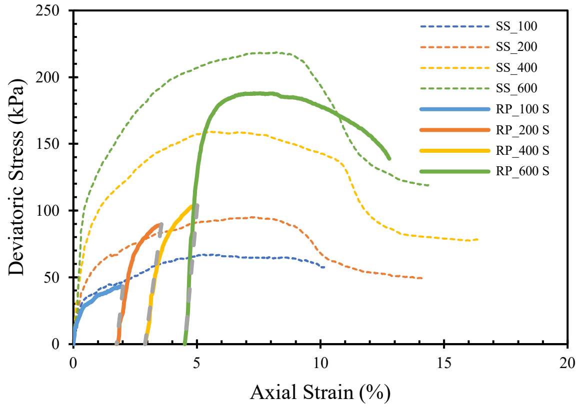

Figure 11. Ankara clay drained response in Single-Stage vs. Rational procedure Sustained

3.2.2. Single-stage vs. Minimum slope

In drained tests, minimum slope (MS) procedure is found to be more accurate. As it is provided in Fig. 12, for MSC procedure, the peak deviatoric stresses at all four sequences are close to perfect compared to those of the single-stage results. On the other hand, in Fig. 13 the MSS procedure cannot accurately capture the real behavior of the reconstituted Ankara clay specimen. At third sequence the peak deviatoric stress was found more than the single-stage test results and at fourth sequence the strength was much lower than the expected value and even less than the third sequence results. The great strength loss at fourth sequence can be due to excessive deformation and development of failure planes. Therefore, the fourth sequence is not considered for MSS in Fig. 14 and 15 and there are three data points.

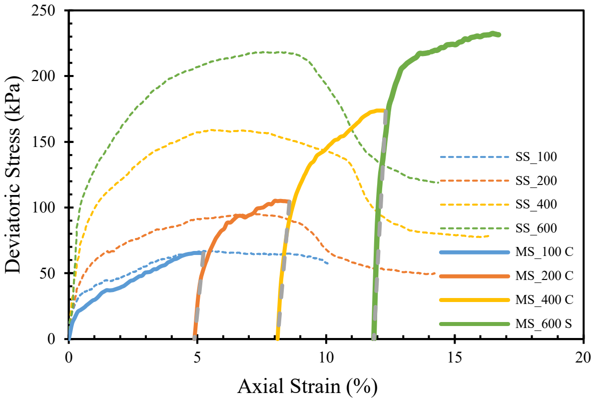

Figure 12. Ankara clay drained response in Single-Stage vs. Minimum slope cyclic

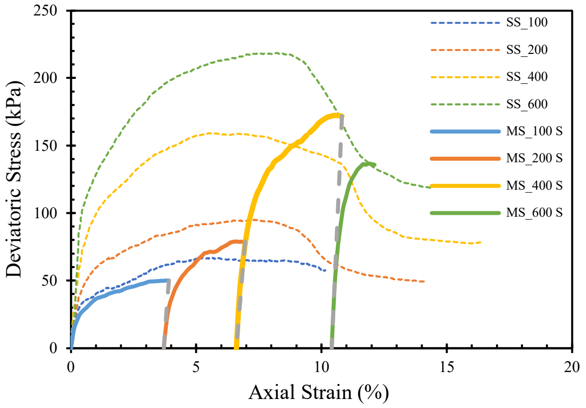

Figure 13. Ankara clay drained response in Single-Stage vs. Minimum slope Sustained

3.2.3. Drained outcome compatibility

In addition to deviatoric stress-axial strain response of the specimen at each procedure, the secant elastic modulus is also investigated for single-stage and multistage procedures in drained tests. From Fig. 14 obtained secant elastic modulus from single-stage and MSC procedure are very close except the first sequence that E'_{50} for MSC and single-stage are 2.8 MPa and 7.5 MPa respectively.

In Fig. 15 the modified failure envelopes for single-stage and multistage procedures for drained tests are demonstrated and strength parameters are presented in Table 4. Although the strength parameters found from RPS seem to be close enough to single-stage results, by considering the low R-square and high variation of data from the fit line (Fig. 15), MSC is more reliable for drained tests. The secant elastic modulus from Fig. 14

supports this idea. The MSC procedure gives accurate result referred to the single-stage testing results in terms of the strength parameters (c′ and ϕ′) and secant elastic modulus.

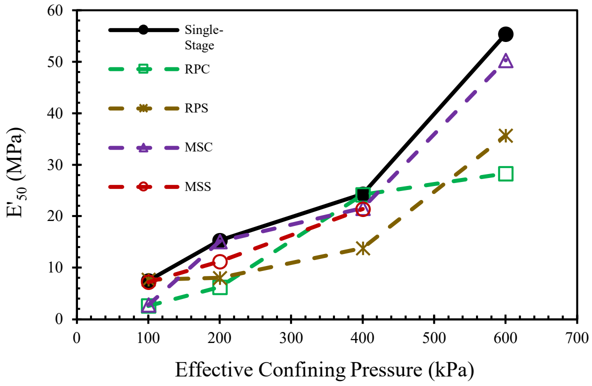

Figure 14. Secant elastic modulus E'_{50} for single-stage and multistage drained tests

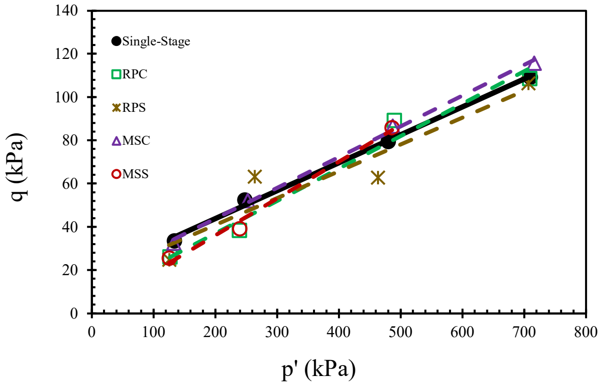

Figure 15. Modified effective strength envelope from single-stage and multistage drained tests

Table 4. Drained strength parameters obtained from single-stage and multistage procedures

Test	Loading	Internal friction angle (◦)	Cohesion (kPa)
Single-stage	-	7.7	16
Rational procedure	Cyclic	8.6	7.2
Minimum slope		8	15.5
Rational procedure	Sustained	7.1	16.2
Minimum slope		10	1.5

4. Conclusion

Objective of present study is to identify the most accurate and applicable multistage triaxial procedures on reconstituted Ankara clay. An alternative testing procedure for undrained and one for drained tests are suggested to overcome the limitations of the conventional triaxial testing method. By employing these procedures using only one specimen, the issues associated with sample scarcity, soil variability and expensive triaxial tests are answered and soil strength parameters can be found in a more reliable and timely manner. A series of undrained and drained multistage triaxial tests are performed on reconstituted high plasticity Ankara clay sample under two deviatoric loading conditions. The results are compared by single-stage conventional undrained and drained test results on identical specimens and effective confining stresses of 100 kPa, 200 kPa, 400 kPa and 600 kPa. The most accurate multistage procedure is sought in terms of internal friction angle, soil cohesion, Skempton's (1954) pore pressure parameter A and the secant elastic modulus E'_{50}. It is concluded that the rational procedure with cyclic loading and minimum slope with cyclic loading can be perfectly applied on high plasticity reconstituted Ankara clay for undrained and drained tests respectively. Friction angle and soil cohesion are found as 7.6◦ and 22 kPa for undrained single-stage test, whereas these parameters are obtained as 7.4◦ and 23 kPa employing the rational procedure under cyclic loading condition. Pore pressure parameter A and elastic modulus E'_{50} variations under different effective confining stresses from rational procedure cyclic loading matches well with single-stage conventional triaxial test results in undrained tests.

For the drained test, minimum slope with cyclic loading condition is the best applicable multistage procedure on reconstituted Ankara clay soil specimens. Strength parameters (ϕ′ and c′) found from drained single-stage experiment are 7.7◦ and 16 kPa. Estimated effective internal friction angle and soil cohesion obtained from minimum slope with cyclic loading are 8◦ and 15.5 kPa which are in good agreement with the single-stage test results. Also, the secant elastic modulus from minimum slope with cyclic loading is very close to the secant elastic modulus from single-stage test.

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