Comparison of residual shear strength determined by different methods

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ABSTRACT

The shear stress of stiff or dense soils increases with the displacement and reaches its maximum value, and then shear stress decreases and remains a constant value. The minimum and constant shear stress of soils reached at large shear displacements is called as residual shear strength. Residual shear strength generally has a great importance in design of engineering structures constructed on fissured overconsolidated clays and long-term slope stability analysis in geotechnical engineering. In laboratory testing, modeling the residual conditions of a soil requires large shear displacements attained in drained conditions. Reversal direct shear test (RDS), consolidated-drained triaxial test (CD) and torsional ring shear test (RS) are the widely used testing methods to determine residual shear strength parameters. These methods have some advantages or limitations when compared with each other. In this study, residual shear strength parameters of soil samples having different clay fractions were determined by the three different drained tests, the results were compared, and effect of the testing methods on residual shear strength was investigated. The variation of residual shear strength angle versus liquid limit and plasticity index were studied. The results were compared with previous studies. As a result, it is found that the residual shear strength angle determined by the ring shear test is lower than the others, and the residual shear strength angle decreases with the increasing liquid limit and plasticity index.

INTRODUCTION

When the stress-strain relationships of soils are investigated it can be seen that the shear stress increases with the deformation and reaches to a peak value, then gradually decreases to a constant value. While the peak value of the shear stress is known as shear strength, the minimum and constant value of shear strength is defined as residual shear strength [1]. As the residual shear strength is attained at large shear displacements, it is useful for slope stability analysis of fissured-hard clay soils and the progressive failures due to the strength reduction with time. Soil type, mineralogical structure, level of effective stress and shear rate are the main factors affecting on the residual shear strength. In addition, the testing method used to determine the residual strength is affecting to the residual shear strength parameters [2].

Stress-strain behavior of soils and shear strength parameters can be obtained with laboratory test methods. Consolidated-drained triaxial compression (CD) test, reversal direct shear (RDS) test and torsional ring shear (RS) test are widely used to determine the residual shear strength parameters in the laboratory conditions [3,4,5]. These methods have some advantages and limitations compared with each other. The applicable continuous deformation is limited in consolidated-drained triaxial test and reversal shear test while it is unlimited in ring shear test. The cross-section area of the shear plane and vertical stress acting on the sample are not uniform in consolidated-drained triaxial test and reversal shear test whilst they are uniform in ring shear test. As a superiority of CD test compared with others the stress conditions on the site could be applied on the sample properly during the test [6,7,8]. Widely usage of the test equipment and easiness of the test setup are the main advantages of the RDS. In Turkey, reversal direct shear test is commonly preferred to determine residual shear strength parameters as it is simple to apply [9]. In this study, in order to determine the residual shear strength and to investigate the effect of the testing methods on the residual shear strength CD, RDS and RS tests were carried out on five soil samples having different geotechnical properties, and the test results were compared. Soil samples were prepared in Standard Proctor density, and over consolidation ratio is kept constant during the all tests. The relation between soil index properties and residual shear strength parameters obtained from tests were studied and compared with the results obtained from past studies.

EXPERIMENTAL STUDY

Geotechnical Properties of the Samples

To find out the residual shear strength parameters of five samples prepared by fine grained soils with different clay contents and index properties, consolidated-drained triaxial compression, reversal direct shear and ring shear tests were performed. Wet sieve analysis, hydrometer analysis, consistency limits and pycnometer test were performed to determine the geotechnical properties of each sample. Coarse grain size particles were limited by fine sands up to 10% while the fraction of clay particles in the soil samples range in between 20%-32%. The liquid limits of the samples (w_L) change in the range of 48%-113% and the plasticity index (I_P) values are between 28% and 79%. The specific gravity of the samples ranges between 2.71 and 2.76. The soil types of the samples were determined according to the Unified Soil Classification System as one was low plastic clay (CL) and the others were high plastic clay (CH) [10]. For every soil samples maximum dry unit weight and optimum water contents were determined by standard proctor test. Consequently for determination of the residual strength of these soils, soil samples were prepared with the standard proctor energy at the optimum moisture content in the proctor mold. Due to the type of test method, the required dimensions of soil samples were obtained by either penetrating the highly polished and silicon grease coated rings or trimming.

Consolidated-Drained Triaxial Test

In the consolidated-drained triaxial system, experiments were carried out on samples with a diameter of 50 mm and a height of 100 mm. The samples were prepared at the same conditions. The consolidated-drained triaxial test equipment used in this study is shown in Figure 1. Consolidated-drained triaxial compression experiment was carried out at least on two samples under different confining pressures. After the saturation process of the test, the soil samples were loaded vertically at a rate of 0.008 mm/min which were predetermined from consolidation coefficient of the consolidation tests not to generate excess pore water pressure during the whole test [10]. The excess pore water pressure was observed from the pore water pressure transducer connected to bottom base cap of the sample. The tests were extended to achieve maximum applicable vertical deformations. The vertical deformation, deviator pressure and excess pore water pressure were recorded by ELE data acquisition system at pre-designated time intervals. It illustrated that the peak deviator stresses were observed at about 3% vertical deformations whilst after 20% vertical deformation deviator stress plots were assumed as residual. During the tests in progress no remarkable change in pore pressure were observed. The residual shear strength parameters of the sample were determined by Mohr-Coulomb shear failure envelope plotted on shear stress versus normal stress graphs. The result of consolidated-drained triaxial test performed on a sample was given in Figure 2.

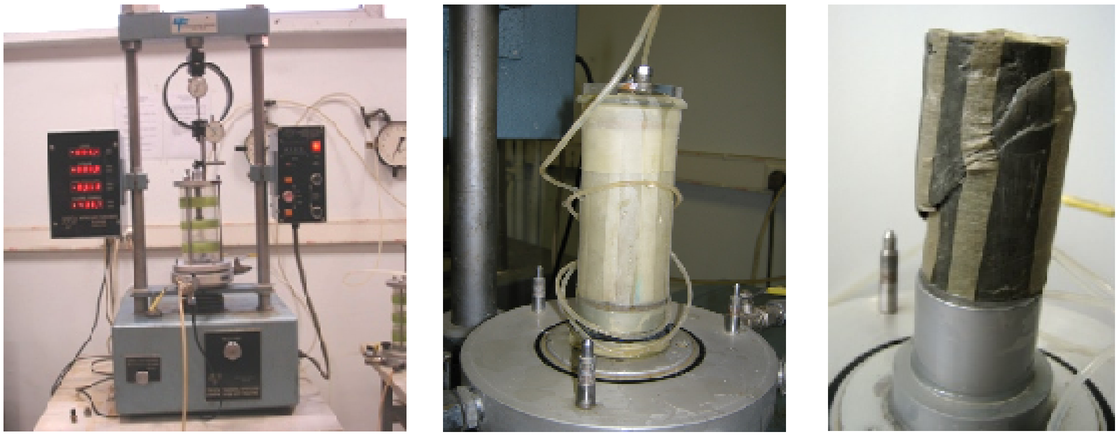

Figure 1. Triaxial compression test equipment used in the study and the specimen before and after test

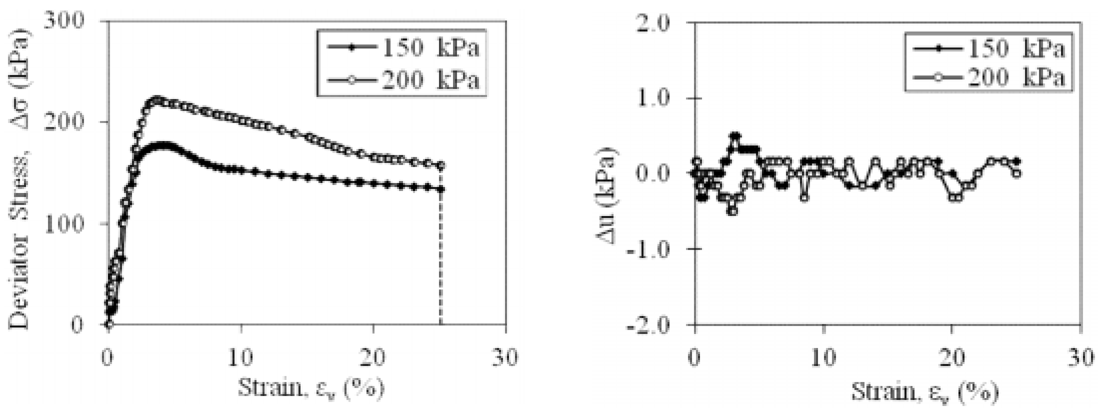

Figure 2. Consolidated-drained triaxial test result of a sample

Reversal Direct Shear Test

In this study the reversal direct shear test was chosen because of its simplicity in sample preparation and testing. It is commonly used method to determine the residual shear strength parameters in our country. Reversal direct shear tests were performed on the prepared soil samples. The reversal direct shear test equipment used in this study and a slickensided shear surface of a sample obtained after the test were shown in Figure 3. The tests were performed on 25 mm thick samples with 60 mm × 60 mm cross-sectional area. Before the shearing process, the specimens were subjected to the vertical consolidation pressure, predetermined as 100 kPa, 200 kPa and 300 kPa for 24 hours. The shearing process was conducted at 0.035 mm/min rate of displacement. To determine the drained residual shear strength of the sample after the test equipment reached its maximum allowable lateral displacement of 12 mm, by reversing the lower ring to the initial position, the specimen was re-sheared a number of times in the same direction [6]. In the scope of this study it was assumed that after the fifth cycle of the shearing process the residual value of the shear strength was attained. Before each cycle, sample was subjected to vertical consolidation pressures for more than 16 hours.

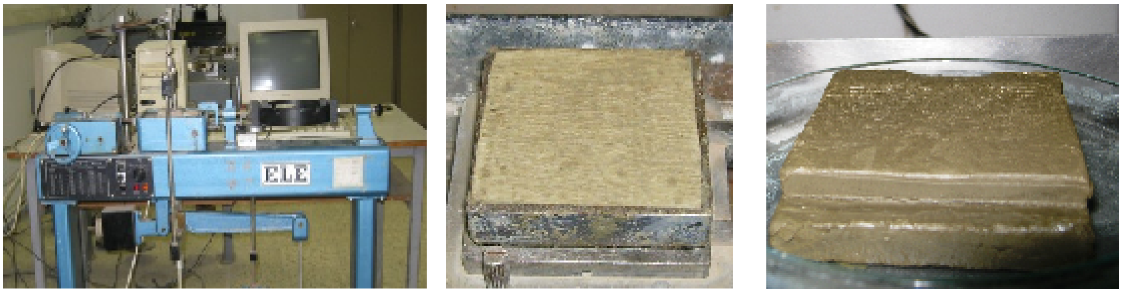

Figure 3. Reversal direct shear apparatus and specimen after the test

Shear stress versus displacement graph of a sample shown in Figure 4 illustrates that in the first cycle of the test for three of the consolidation pressures peak shear stresses were observed at less than 4% lateral deformation. Furthermore the peak stresses and the lateral deformation at this stress decreases as the number of the shearing cycle increases. The residual shear strength illustrates almost no reduction after forth cycle for this sample. The residual shear strength parameters of the soil samples were determined according to the Mohr-Coulomb failure criteria by using the residual shear stresses observed at fifth cycle of shearing.

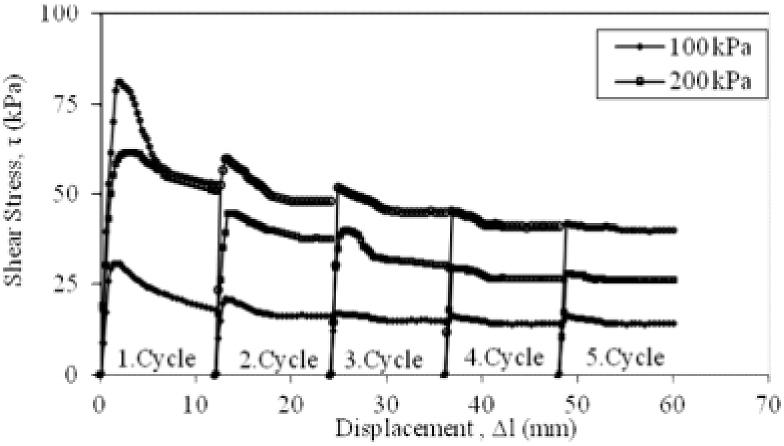

Figure 4. Reversal direct shear test results of the same sample

Ring Shear Test

The ring shear test equipment shown in Figure 5 was used in this study. 20 mm thick ring shape specimens within 150 mm inner and 100 mm outer diameter was prepared three times to perform the test at three vertical consolidation pressures (100, 200 and 300 kPa). After consolidation processes in the system, by rotating lower platen versus the fixed upper platen an unlimited shear displacement was applied to the specimen continuously at a rate of 0.02 mm/min [11]. So the shear plane was formed at around the middle height of the sample. The polished and slickensided surface of the shear plane of a sample after test was also given in Figure 5.

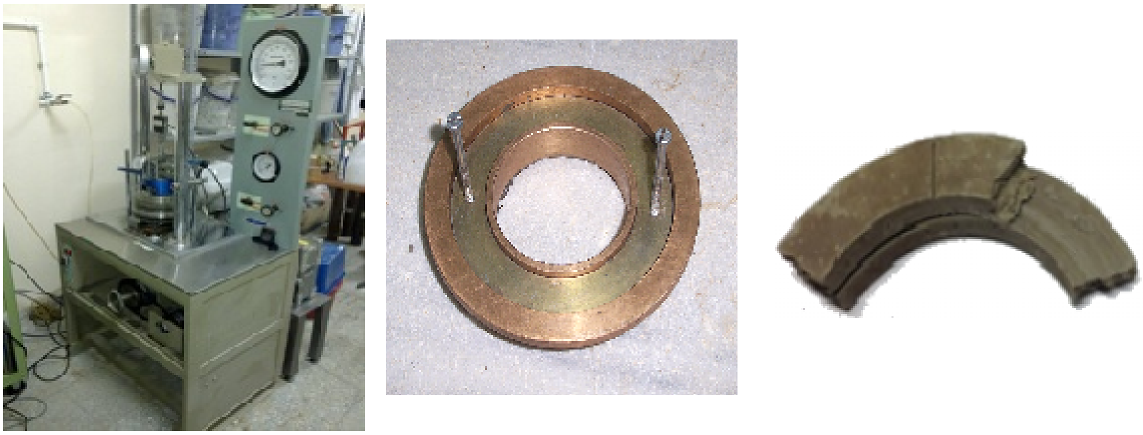

Figure 5. General view of torsional ring shear apparatus and general view of specimen after the test.

During the test under a constant vertical stress at desired interval of times, shear force, side friction, vertical and lateral displacements were displayed continuously with four channel amplifier and recorded by National Instruments data acquisition system. As an example, the shear stress versus shear displacement graph of a ring shear test performed on a sample is shown in Figure 6.

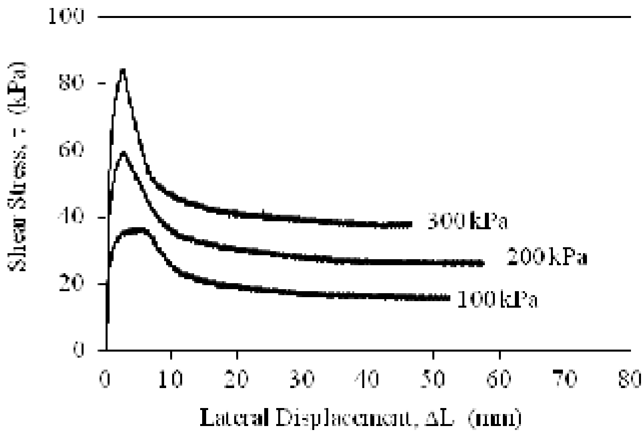

Figure 6. Ring shear test results of the sample

TEST RESULTS AND DISCUSSION

It is known that the residual shear strength of the soils is caused by friction resistance between grains reoriented as parallel to the failure plane attained by large displacements. Residual shear strength is affected by soil structure, mineralogy, normal stress level and shear displacement rate, etc. While the grain size decreases which means specific surface increases, liquid limit is also expected to increase. From that point further consistency limits should be kept in mind as a pointer of the mineralogy. In this study, consolidated-drained triaxial, reversal direct shear and ring shear tests were carried out on five soil samples having different clay fractions and plasticity indexes. The residual shear strength parameters obtained from consolidated-drained triaxial compression, reversal direct shear and ring shear tests were given in Figure 7. As can be seen from the figure, there are a good agreement among the result of different test carried out to determine the residual shear strength angle, ϕ_r. The residual shear strength angle obtained by consolidated-drained triaxial compression tests is slightly greater than the others.

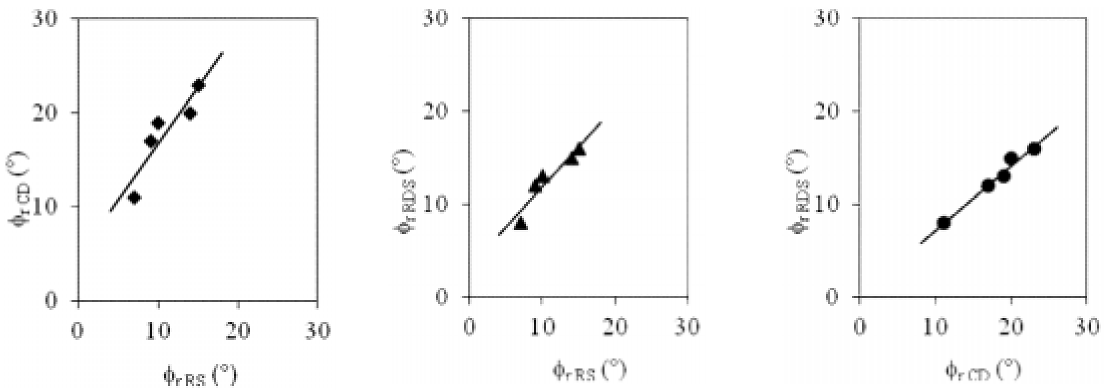

Figure 7: Comparison of ϕ_r values obtained by three testing method

In the scope of this study the variation of the liquid limit (w_L) versus the residual shear strength angles (ϕ_r) determined by consolidated–drained triaxial compression, reversal direct shear and ring shear tests performed on five soil samples is shown in Figure 8. This figure illustrates that the test method affect the residual shear strength angle. Furthermore the residual shear strength angle decreases with increasing liquid limit. Although the shear displacement rates are rather different, the residual shear strength angle determined by ring shear test is a few degrees lower than the obtained by the others method, but it is seen that there is a parallelism between the results.

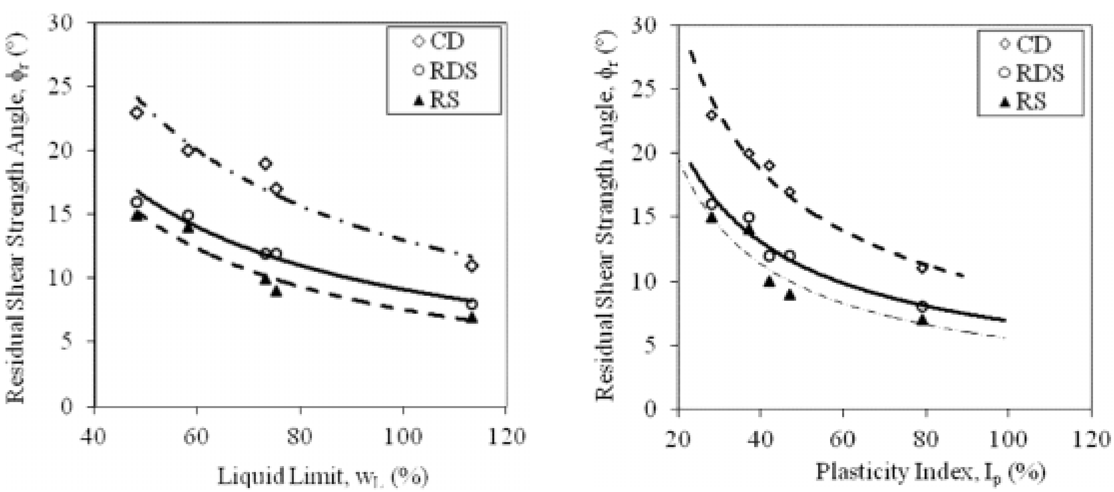

Figure 8. Variation of residual shear strength angle with liquid limit and plasticity index

The variation of the plasticity index (I_p) of the samples ranging between 28% - 79% and the residual shear strength angles determined by consolidated–drained triaxial compression, ring shear and reversal direct shear tests are also given in Figure 8. The plots illustrates that the residual shear strength decreases with plasticity index for three kinds of test methods.

This study illustrates the residual shear strength parameters of the same soil samples determined by consolidated-drained triaxial, reversal direct shear and ring shear tests performed. The variation of residual shear strength angles with liquid limit and plasticity index was investigated.

The comparison of the findings with other studies is given in Figure 9. It is seen that the residual shear strength angles obtained by ring shear test were placed under the curves proposed by Suzuki (2005), Mesri and Capeda Diaz (1986), and Cancelli (1977) [12,13,14]. While the angles determined by reversal direct shear test was above the curve proposed by Cancelli, they are below the Mesri's curve for higher liquid limit values. The residual shear strength angles obtained by consolidated-drained triaxial test were placed above all the curves. It is thought that the difference is caused by the test method.

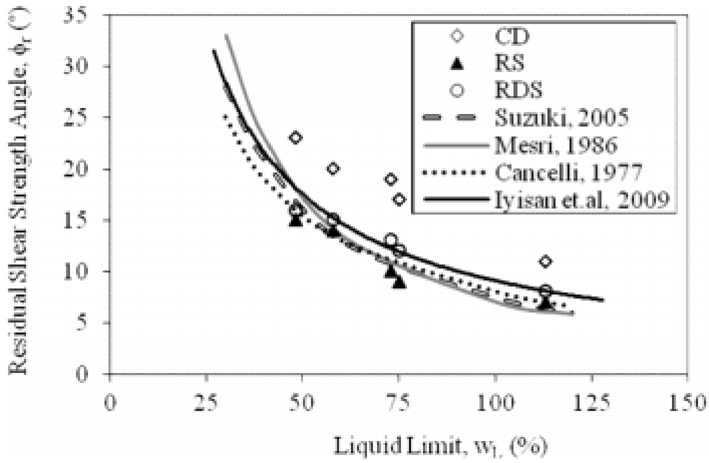

Figure 9. Comparison of the residual shear strength angle obtained from this study with the previous studies

CONCLUSION

Consolidated-drained triaxial compression, ring shear and reversal direct shear tests are the test methods to determine the residual shear strength parameters of the soils. Each method has advantages and limitations. In consolidated-drained compression triaxial test site conditions can be modeled, but there is a limitation in applicable deformation to the sample. During reversal direct shear test, the varying cross sectional area, reorientation of the major stresses and stress concentration at the sample boundaries. During the ring shear test, the area of contact on the shear plane remains constant, applying an unlimited rotational shear displacement to the specimen continuously. In this study to determine the residual shear strength angles, consolidated-drained triaxial, ring shear and reversal direct shear tests were performed on soil samples having different index properties.

The test results show that the highest residual shear strength angle (ϕ_r) was obtained by the consolidated-drained triaxial tests, and the residual shear strength angle obtained by the ring shear test is lower than one obtained by the reversal direct shear test. The residual shear strength decreases with the liquid limit and the plasticity index. These findings based on the limited number of samples, it is possible to develop the findings by performing additional tests on different index properties of soil samples.

REFERENCES

[1] Skempton, A.W., (1985) Residual strength of clays in landslides, folded strata and the laboratory. *Geotechnique*, Vol.**35**, No.1, 3-18.

[2] Mitchell J. K**. (**1993) *Fundamentals of Soil Behaviour*. John Wiley & Sons, New York.

[3] Mesri, G. and Shahien, M., (2003) Residual shear strength mobilized in first time slope failures. *Journal of Geotechnical and Geoenvironmental Engineering.* **129** (1), 12-31.

[4] Sridharan, A., ve Rao, P. R. (2004) Discussion: residual strength of clays and correlation using Atterberg limits" *Geotechnique,* **54**, No 7, 503-504.

[5] Dewoolkar M.M. and Huzjak, J.R. (2005) Drained residual shear strength of some claystones from front range, Colorado. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. **131**, No12.

[6] Suzuki, Tsuzuki, S., and Yamamoto, T. (2008) Residual strength characteristics of naturally and artificially cemented clays in reversal direct box shear test. *Soils and Foundations*, **47**(6), 1029-1044.

[7] Thiel, R. (2009) Cohesion and friction angle in direct shear tests. *Geosynthetics*,

[8] Tiwari, B and Marui, H. (2005) Comprasion of residual shear strengths form back analysis and ring shear tests on undisturbed and remolded specimens. *Journal of Geotechnical and Geonvironmental Engineering.* Vol. **131**, No.9, pp, 1071-1079.

[9] İyisan, R., Çevikbilen G., Koltuk S., Yılmaz E., (2006) Measurement of residual shear strength by ring shear test. *Seventh International Congress on Advances in Civil Engineering*, Yildiz Technical University, Istanbul, Turkey..

[10] Bayın, A., (2010) Determination of residual shear strength by consolidated-drained triaxial test. MSc Thesis, Istanbul Technical University, Turkey.

[11] ASTM D 6467. (2000) Standart test method for torsional ring shear test to determine drained residual shear strength of cohesive soils. *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, USA.

[12] Suzuki, M., Tsuzuki, S., ve Yamamato, T. (2005) Physical and chemical index properties of residual strength of various soils. http://donald.lib-e.yamaguchi-u.ac.jp/hokoku/561/01.pdf

[13] Mesri, G. and Capeda-Diaz, A.F., (1986) Residual shear strength of clays and shales. *Geotechnique*, **Vol.36**, No.2, 269-274.

[14] Cancelli, A., (1977) Residual shear strength and stability analysis of a landslide in fissured overconsolidated clays. *Bull. Int. Assoc. Eng. Geol*., **Vol. 16**, 193-197.