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Determination of Residual Shear Strength from Reversal Direct Shear test: Analysis and Recommendation

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Abstract: ***Reversal Direct Shear test is used for the determination of residual strength of soil sample. This test was conducted on the undisturbed and remolded sample of embankment slope of Pa Bon Dam, Thailand that had failed after its operation for 10 years. The undisturbed sample was taken from the downstream slope (non-failure zone) while the remolded sample was taken from the upstream slope (failure zone). The results yielded the identical values of residual strength parameters. On the basis of laboratory test, various recommendations are proposed for the conduction of this test in future.***

Keywords: ***Residual Strength, Reversal Direct Shear Test, Remolded and Undisturbed Soil Sample, Sample Loss, Shearing Rate***

I. INTRODUCTION

Residual strength is the minimum constant shear strength attained in a soil at large displacement under given effective normal stresses and reversal technique can be used for determining residual strength as it provides a satisfactory result with equipment available in every laboratory [1]. In case of the slope which has already failed, the subsequent movement of the slope is determined by the residual strength of the clay. Residual Strength can be obtained by using multiple- reversal direct shear test or ring shear test by shearing the specimen at very large displacement. Since the magnitude of the shear displacement available in direct shear box is small, more than one travel is needed to obtain residual strength of any soil. It can be achieved by returning the box into its starting position and the process is completed by repeating the process number of times. Residual strength can also be determined by using ring shear test [2-5]. The results obtained from reversal direct shear test and ring shear test was found to be identical as shown in **Fig. 1**.

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The breakdown of bonds between clay particles in reversal direct shear test is higher than its restoration for higher shear rate, and hence lower shear strength is obtained [6]. Likewise, the vertical displacement is observed due to loss of soil in the center gap in the shear box [7]. Hence, precutting specimen has a slight advantage due to the proper alignment of particles on both side of shear plane and generation of horizontal and planar shear surface [7, 8]. Fast shearing followed by slow shearing gives a steady shearing strength and lowest value of residual strength. This method is less time consuming and does not require skilled operator for preparation of precut samples [9, 10]. Similarly, for lower shear rate, the recovery rate is similar to the breakdown rate [11]

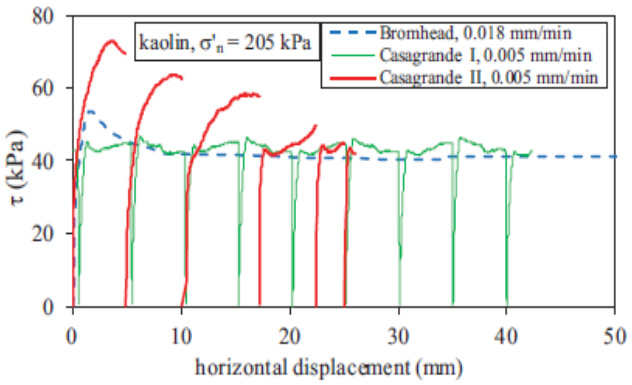

Fig. 1: Shear Strength against horizontal displacement for Kaolin [12]

Rate of shearing needs to be considered before the conduction of laboratory tests and various shearing rates have been adopted in the past [10, 12, 13]. The residual shear strength is obtained when the displacement rate is in the range of 10^{-6}-10^{-1} [12]. The change in rate of horizontal displacement from 0.02mm/hr to 2m/hr increases the shearing resistance by approximately 3 kPa i.e. around 10% [7]. The shear rate and Over-consolidation ratio(OCR) have very negligible influence on the residual strength [1, 4] . Empirical relationship for the estimation of residual friction angle on the basis of basic soil parameters has also been estimated by various researchers in the past [4, 14].

II. BACKGROUND

Pa Bon dam, located at Phatthalung Province, Thailand, is a 45m high zoned embankment dam. The operation of dam started in 14th January, 2004 and was operating without any hindrances up to the year 2014.

In 2014, the physical movement was observed in the upstream slope of dam for the first time (**Fig. 2**) and is continuing till date. It was assumed that the strength of soil has reduced from peak to residual state at the time of failure causing the movement of upstream slope.

Fig. 2: Pa Bon dam after its movement on 14th January, 2004

Reversal direct shear test was used for the determination of residual strength of soil sample. The test was conducted for two soil samples taken from upstream slope i.e. Failure Zone and downstream slope i.e. Non-Failure Zone. The collection of undisturbed sample from the failure zone was not possible, so the test was conducted using the remolded sample while undisturbed soil sample was collected from the downstream slope. The sample from downstream slope was collected at same elevation and chainage as that of upstream slope. It was done to analyze the change in strength parameters at the section where it had the impact of water level fluctuation (upstream slope) and where it did not have the influence of water level (downstream slope).

III. LABORATORY TEST

Reversal Direct Shear test was conducted to determine the residual strength of embankment slope. Overall 4 set of tests were conducted but results from only 2 set were taken into consideration. The recommendation is based on the problems encountered during the conduction of these tests. Steps followed for the conduction of this test is explained below.

A. Calibration

Load Cell, Vertical Displacement Transducer and Horizontal Displacement Transducer were calibrated before the conduction of direct shear test. The calibration was conducted via DS7 software. The use of calibrated load cell and transducer is essential to determine the exact displacement on the basis of load applied.

B. Procedure

Reversal direct shear test was conducted for two samples obtained from Failure Zone and Downstream Slope; samples collected were Remolded and Undisturbed respectively. For the undisturbed sample, the size of sample collected was less than 75mm. The sample was oven dried and sieved with sieve No. 40 (425 μm). The sample was then mixed with water content for maximum dry density obtained from standard compaction test (i.e. 29.47%); the moisture content used was similar to that of failure zone i.e. 29.66%. The sample was compacted to 95% of maximum dry density (1.69g/cc) to simulate the exact site condition. The procedure hereafter was similar for both undisturbed and remolded soil sample. Methods proposed by K.H. Head was used for the determination of residual shear strength [15].

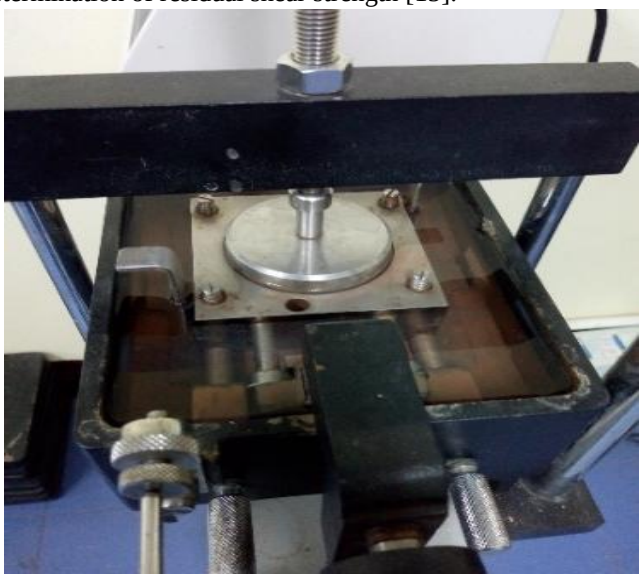

Fig. 3 : Apparatus setup for conduction of Direct Shear Test

Fig. 4: DS7 Software for Monitoring Test Results

After the preparation of sample, it was kept in the direct shear box and was soaked for 24 hours (**Fig. 3**). After soaking the sample, it was allowed for consolidation until the constant value of vertical displacement was observed. In general, all the samples used were completely consolidated in 24 hours but it cannot be taken as standard consolidation time. It varies according to the index property of sample. The data obtained from consolidation was recorded via DS7 software (**Fig. 4**). The rate of shearing was calculated from the results obtained from consolidation test on the basis of ASTM D3080.
Consolidation state was followed by shearing state. The sample was sheared until peak shear strength was obtained followed by the decrease in shear strength. If the consolidation data is not recorded correctly, the rate of shearing will not be accurate and the peak value might not be obtained even after standard shearing displacement.

In laboratory, the soil sample was sheared for 5-6mm so that there will be minimal loss of soil sample. After complete forward shearing, the machine was reversed in opposite direction. The rate of shearing was based on time taken for soil sample to reach the failure state. Shearing rate for backward shearing is faster than the rate of forward shearing [15].

After bring the sample back to its original position, it was left there for 24 hours to maintain the water equilibrium. The shearing was continued for many cycles using the above procedure until the constant value of shear strength was obtained. In this case, six cycles were conducted for each normal load and was followed by test of pre-cut specimen. The result from precut specimen was consistent with the results obtained from intact specimen. The numbers of loads applied for each case were 2kg, 4kg, 6kg and 8kg respectively

C. Results:

The results of shear stress vs horizontal displacement for failure zone and downstream slope is shown in **Fig. 5** and **Fig. 7** respectively. Similarly, the result for normal stress vs shear stress is shown in **Fig. 6** and **Fig. 8** respectively. The result obtained from reversal direct shear test is presented in Table I. From the result, it was observed that the residual strength of soil is independent of specimen type while peak strength of remolded sample is higher than undisturbed sample. It is due to the fact that remolded specimen is compacted uniformly in laboratory giving higher peak shear strength.

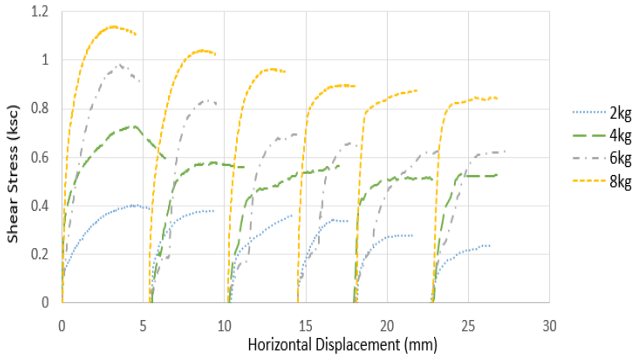

Fig. 5: Shear Stress vs Horizontal Displacement for Failure Slope

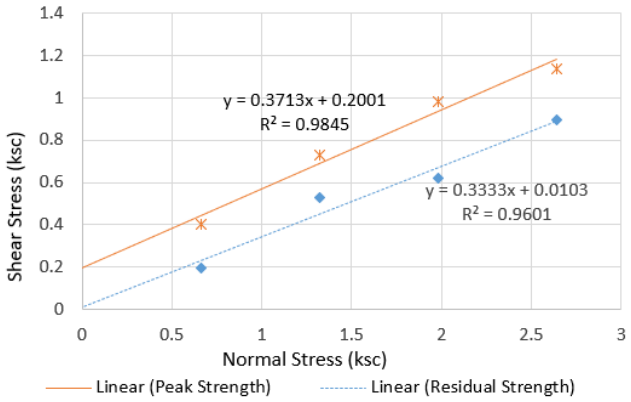

Fig. 6: Shear Stress vs Normal Stress for Failure Slope

Likewise, upstream slope had an impact of water level fluctuation but downstream slope did not encounter such condition and from the results it was found that that the fluctuation of water is independent of residual strength. Theoretically, cohesion value should be zero for residual strength but certain value was obtained for all cases even in the case of precut specimen.

Table I: Results from Reversal Direct Shear Test

S. No.	Test Location	c'p (kPa)	Φ'p	cr (kPa)	Φr
1	Downstream Slope (Undisturbed Sample)	18.93	19.24	0.67	17.63
2	Upstream Slope (Remolded Sample)	20.01	20.36	1.03	17.45

For obtaining the above results, 4 sets of reversal direct shear test were conducted. The results obtained from initial 2 tests could not be used due to high loss of sample, error in data collection and shearing rate. The recommendations based on various sets of test are presented in section below.

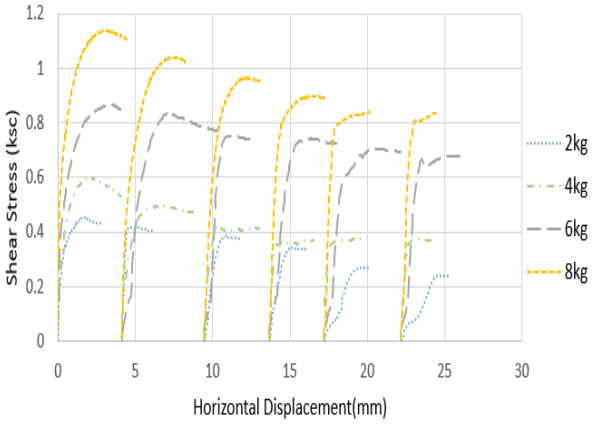

Fig. 7: Shear Stress vs Horizontal Displacement for Downstream Slope

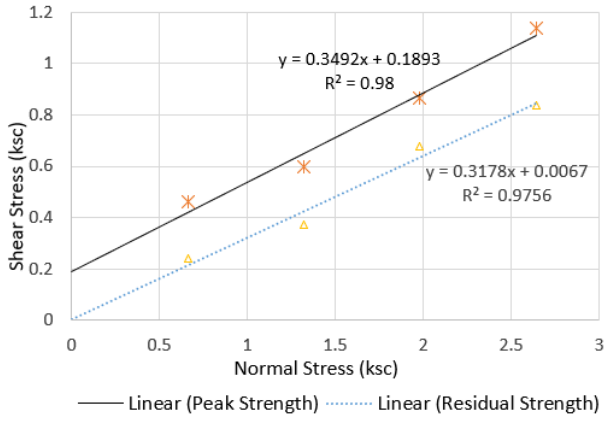

Fig. 8: Shear Stress vs Normal Stress for Downstream Slope

IV. RECOMMENDATIONS

During the reversal direct shear test, one of the major problems was the loss of soil sample during multiple shearing cycles. Various recommendations are proposed to overcome this problem in future.

A. Use of Filter Materials

Filter paper was used for the first cycle of reversal direct shear test (**Fig. 9**) but with multiple shearing cycles, the loss of sample was very high because water was not filtered properly. To overcome this problem, porous stone was used from next shearing cycle (**Fig. 10**) for filtering process. The loss of material using porous stone was comparatively lower than that of filter paper. The porous stone of 3mm height was made with sand samples retained in #30mm sieve. The porous stone was made from the mixture of sand, 3% Hardening chemical and 5% dispersing agent (polymetaphosphate). After its preparation, it was kept in vacuum chamber and air bubbles were removed using vacuum pump. The stone was used after saturating it for 48hours. The path for passage of water was eased with the use of porous stone and the loss of sample was considerably reduced. The strength of the porous stone should be designed on the basis of normal load used.

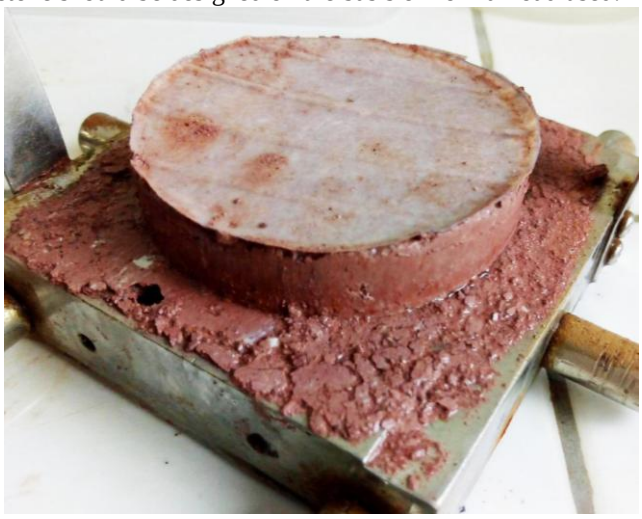

Fig. 9 : Filter Paper used as Filtering Material

Fig. 10 : Preparation of Porous Stone

B. Shearing Rate

From previous research works, it was found that fast shearing followed by slow shearing helps in saving time and provides similar result [9, 10]. Similar procedure was used for determination of residual strength where shearing rate was obtained from ASTM D2435/D2435M−11. Shearing rate of 0.005mm/min was used for first and second cycle followed by shearing rate of .05mm/min for next four cycles but during those cycles, loss of sample was distinctly observed in direct shear box. In most of the cases, even though distinct vertical displacement was not recorded in DS7, the loss of soil sample was clearly observed as shown in **Fig. 11**. It was due to the fact that displacement in DS7 is measured only at the center of sample. The recovery rate is similar to breakdown rate for lower shearing rate [11] and hence use of slow shearing rate gives trustworthy result. It was found that the shearing rate is directly proportional to the loss of sample and is recommended to use slow shearing rate for reversal direct shear test.

Fig. 11 : Loss of sample from fast shearing (0.05mm/min)

C. Backward Shearing

K.H. Head has proposed various methods for backward shearing of direct shear box for determination of residual strength [15]. Shearing includes reversing the direction by hand-winding facility within a period of few minutes until original alignment is reached. Likewise, it is also recommended to apply five to ten rapid backward and forward travels to establish the shear plane. These two methods were used initially but loss of sample was observed in both cases while manually reversing the direction. So, it is recommended to reverse the motor in backward direction in such a way that the time taken for reversal travel is about same as time from start of shearing to peak shearing.

D. Pre Cut Specimen

To overcome the problem of sample loss, one of the best methods is to use the pre-cut specimen (**Fig. 12**) but this technique should be performed with higher efficiency. Pre-cutting of the specimen is recommended to be conducted after first shearing cycle. In this manner, peak shear strength of soil sample can be obtained and failure plane for pre-cutting can also be exactly determined. Precutting specimen was observed to have had a slight advantage due to the proper alignment of particles on both side of shear plane and generation of horizontal and planar shear surface [7, 8].

The cut portion of soil sample should be exactly in between the shear box else the failure plane will vary and the results can't be relied upon. For this test, pre-cut sample was used after obtaining the residual strength (after 6th cycle) and it helped in verifying the result obtained from conventional reversal direct shear test

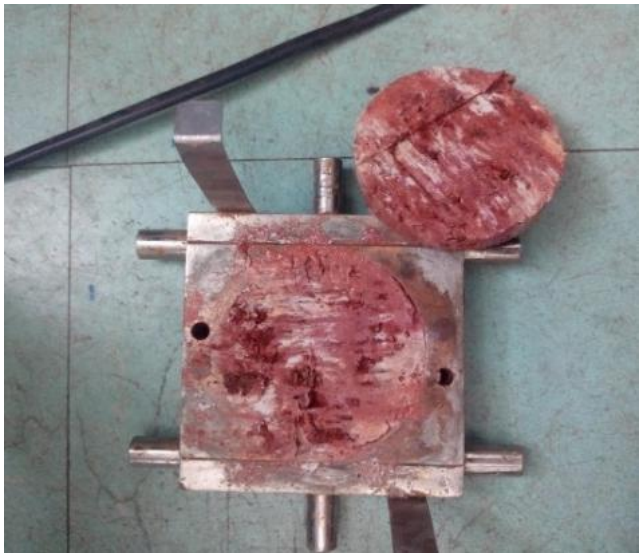

Fig. 12 : Precut specimen after First Shearing Cycle

Likewise, various other problems were also identified and presented in this research work. After the end of consolidation cycle, the value of shear force should be set to zero. Theoretically, there should be no shear force during consolidation cycle but some values are recorded and it's recommended to reset the value before inception of shearing cycle. Similarly, after forward shearing cycle, the box is returned back to its original position. During the reversal cycle, the shear force should be monitored constantly and should be stopped when its value is zero. If it's allowed to reverse from that point, negative value of shear force will be recorded. The negative value is obtained when the shear box moves further and has no contact with the machine as shown in **Fig. 13**. If the machine is not stopped at zero, unnecessary data are recorded; the method is proposed to ease the work.

Fig. 13 : Direct Shear Box after backward shearing

It is also recommended to record all the data of consolidation, forward shearing and backward shearing. Practically, there is no significant use of data from backward shearing but these data might be helpful when we encounter human error during the calculation. Similarly, the number of data to be recorded for shearing and consolidation should be calculated prior to the conduction of test; excess unnecessary data should be avoided. Likewise, shearing plane of the sample should be in between the sample. To identify this point, total consolidation height of the sample should be determined before preparing the soil sample. If the shear plane is not in between the sample, the force will not be equally distributed as shown in **Fig. 14** and results obtained might not be trustworthy while if the shearing plane is at the center of soil sample then the force will be equally distributed as shown in **Fig. 15**.

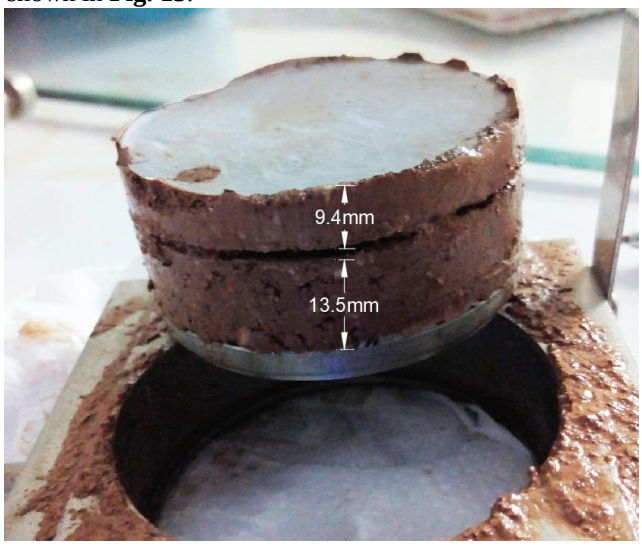

Fig. 14: Shearing Plane after completion Failed Test

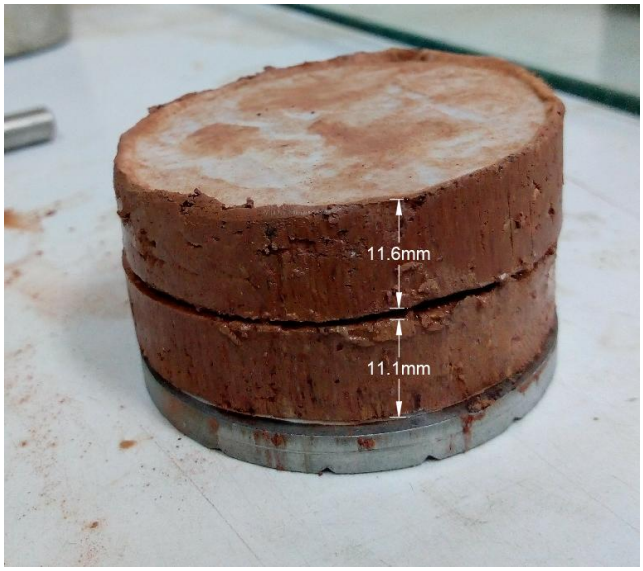

Fig. 15 : Shearing Plane After Completion of successful test

V. CONCLUSION

Residual strength of soil sample can be obtained from reversal direct shear test and following conclusions are obtained from this research work:

1. The residual strength obtained from undisturbed and remolded sample are almost identical.
2. The fluctuation of water level does not have an impact on residual strength.
3. Reversal direct shear test should be conducted with high precision for obtaining accurate results.
4. Various recommendations should be taken into consideration to contain the loss of sample to minimum and avoid human errors.
5. The standard permissible percentage of sample loss during the conduction of this test needs to be identified in future.

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