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Experimental Investigation of Hydro-Mechanical Soil Properties of a Slope Failure

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Keywords

Unsaturated Soils
Matric Suction
Landslides
Slope Stability

Abstract

A sudden slope failure occurred in Manisa possibly due to the effect of water infiltration because of a slightly damaged sewage pipe. Considering that there was no other evidence such as rainfall or any loading conditions to trigger the slope failure, a laboratory investigation on the soil's unsaturated hydro-mechanical properties was initiated. Slopes are naturally unsaturated soils, and they may lose their stability with increased saturation degrees with water infiltration. Thus, for a proper investigation, the unsaturated hydro-mechanical properties of soils should be determined. The results presented in this study are focused on determining the key parameters to evaluate the slope failure for unsaturated soil conditions. In this regard, hydraulic conductivity and suction characteristics and the shear strength parameters were determined as well as the classical geotechnical properties of the soil. Classification of soil was determined as silty sand which is known to have slight to moderate suction stresses and mostly affected suddenly by water infiltration. A flexible-wall permeability test was run with a falling head procedure and the saturated hydraulic conductivity of the soil sample was measured as $1x10^{-7}$ m/s. Suction characteristics were detected by filter paper method, besides, the soil water retention curve of the soil was constructed. The maximum matric suction of the soil was measured as 2887 kPa for an air-dried sample. Following, the shear strength parameters were measured by conventional direct shear test for both dry and soaked conditions. Finally, the friction angle due to suction was calculated to be 1.7 degrees from the results of dry and saturated shear strength parameters.

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1. INTRODUCTION

Slope failures can occur due to many reasons, but one is particularly the interest of this study which is slope failures triggered by water infiltration. Slopes are naturally unsaturated soils; however, the conventional soil mechanics principles handle the slope stability analyses regarding the saturated conditions. Slopes can be stable even at very steep angles when they are unsaturated, and when subjected to an infiltration caused by rainfall, snowmelt or any leakage, then, the same slope may suddenly lose its stability due to the increase in its saturation degree which causes decrease in capillary forces. In literature, there are many examples of failures caused by infiltration (Oh & Lu, 2015; Batali & Andreea, 2016; Xian et al., 2022) and also many studies to predict the event before it happens like early warning systems (Intrieri et al., 2012; Naidu et al., 2018). In addition, there are such modeling studies which aims understanding the behavior of the infiltration caused slope failures (Vanapalli et al., 1996; Zhang et al., 2014; Tang et al., 2018). In fact, using laboratory data is the most convenient way to investigate the stability of a certain slope, it is not very common for practical purposes. Some of the theoretical studies used imaginary soil properties where some of them used real laboratory data or data from unsaturated soil hydraulic database (UNSODA, 2022). The main characteristic properties which affect the slope stability and failure mechanism are known as the matric suction and hydraulic

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conductivity (HC). Concerning the unsaturated soil mechanics, matric suction is a key parameter to enhance the strength and the unsaturated soil strength relations are suggested by Fredlund et al. (1978) as a modified equation given in Equations 1 and 2, in addition, the graphical forms of the relation for both saturated (Figure 1a) and unsaturated soils (Figure 1b) are also given in Figure 1.

$$\tau_f = c' + \left(\sigma_f - u_a\right)_f \tan \emptyset' + (u_a - u_w) \tan \emptyset^b \quad (1)$$

$$c = c' + (u_a - u_w) \tan \emptyset^b \quad (2)$$

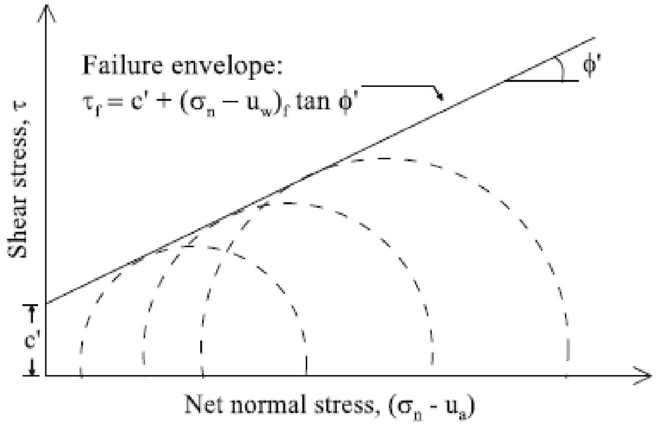
where;

$\left(\sigma_f - u_a\right)_f$ is net normal stress

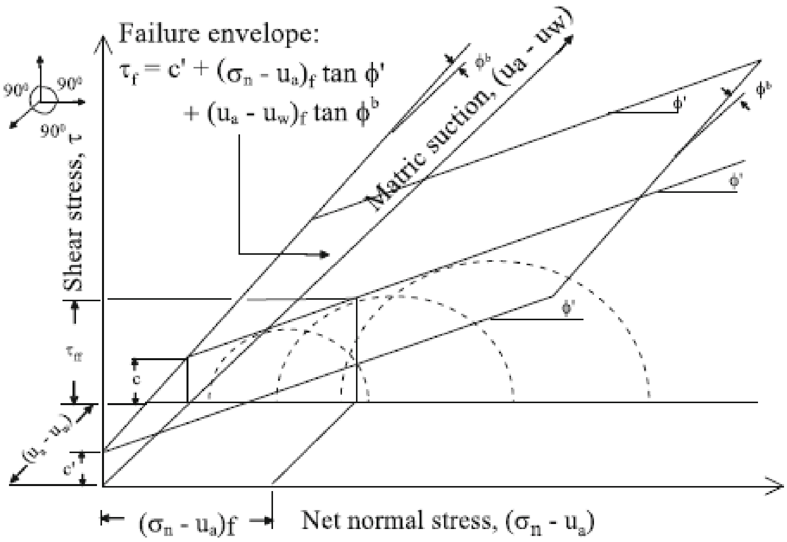
$(u_a - u_w)$ is the matric suction

ϕ^b is the angle which gives the rate of change in shear strength related to the changes in matric suction.

c' and ϕ' are classical effective cohesion and angle of internal friction, respectively.



(a) Saturated soils



(b) Unsaturated soils

Figure 1. *Classical and modified failure criteria of*
a) *saturated soils and* ***b)*** *unsaturated soils (after Chowdhury & Azam, 2016)*

The friction angle due to suction, ϕ^b, is accepted to be constant as shown in Equation1 and Figure 1 and in literature it is generally used as a constant called as the average rate of increase in shear strength relating to matric suction. The results from many reported studies (Gan & Fredlund, 1995; Bai & Lui, 2012; Chowdhury & Azam, 2016) ϕ^b is found to be smaller than ϕ' in addition, according to Gan and Fredlund (1995) ϕ^b approaches to ϕ' with increasing saturation and finally equals when the soil approaches full saturation.

When studying with unsaturated soils it is very important to measure their suction values in order to properly obtain their strength characteristics. The shear strength measurements can be done by modified forms of test apparatus such as direct and ring shear tests and triaxial tests. The modification usually includes a controlled suction measurement system; however, the modifications are mostly expensive and time-consuming so that, separate measurements of suction characteristics and shear strength are still accepted. Oh and Vanapalli (2010) used a modified triaxial apparatus to measure the unsaturated shear strength parameters and investigated the factor of safety of a glacial soil under the rainfall conditions. The axis translation method was applied, and the study also reported a constant ϕ^b although, the change in shear strength relating to matric suction was not linear. Bai and Liu (2012) performed conventional direct shear tests and then, combined the shear strength results with the suction characteristics of findings from filter paper tests. The findings of the study showed the relation between ϕ^b and matric suction, the results implied that, with increasing matric suction ϕ^b decreased and reached very smaller values where it was equal to ϕ' when there was no suction. To combine suction and shear strength tests, a soil water retention curve (SWRC) is usually constructed by measured suction values for corresponding volumetric water contents or saturation degrees to find the desired suction value for a specific volumetric water content or a saturation degree (Fattah et al., 2017). Then, this suction value is related to the strength parameters using Equation1. Thus, an appropriate laboratory work to properly study a stability problem for an unsaturated soil is the key initial situation. The objective of this study is to investigate and find out the hydro-mechanical properties of a soil picked up from a failed slope in Manisa triggered by water infiltration. In this regard, index properties, sieve analysis, Atterberg limits, HC test and direct shear tests (dry and soaked) were conducted. Besides, matric suction measurements were done and SWRC was also constructed.

2. MATERIAL AND METHOD

A slope failure occurred in Manisa after a leakage from a slightly damaged sewage pipe (Figure 2). Considering that there was not any other evidence to trigger the slope failure, an investigation on the soil hydro-mechanical properties was initiated. Sieve analyses was done and Atterberg limits were determined along with the index properties such as unit weight and specific gravity and all the basic geotechnical descriptive properties were presented in Table 1.

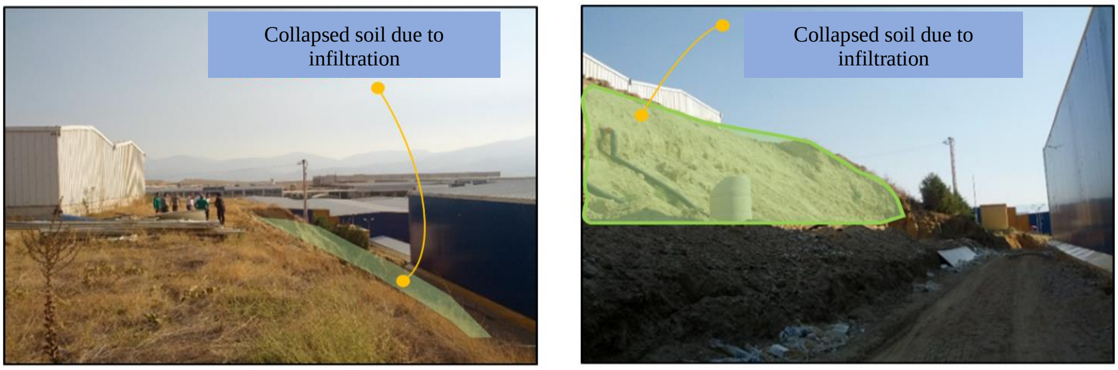


Figure 2. *Condition of the slope*

The saturated HC of the soil was measured by a flexible wall permeameter with falling head procedure (ASTM D5084-16). A soil sample was taken directly from the slope origin and cut into dimensions to fit in the permeameter (Figure 3) and then carefully trimmed to a diameter of 10 cm and a height of 9.6 cm thus, no compaction procedure was followed and, the soil was in its air-dried state. Geotextiles of 10 cm diameter were used as porous material and the HC of the geotextiles were initially found to be 10^{-4} m/s which was convenient to use to determine the HC of the slope soil. During the test, the confining stress was 35 kPa, the average hydraulic gradient was 11 and no backpressure was applied. The flow direction was upwards to avoid any air bubbles and tap water was used during the permeation in addition, the inflow path itself was also flushed avoiding any air bubbles. For the first 24 h, the inflow valves were kept open while the outflow valves were closed which helped the prehydration of the soil specimen for a homogeneous diffusion. The test was lasted at least for 3 pore volumes of flow (PVF) and terminated when the outflow and inflow remained constant for the last 5 consecutive measurements while the ratio of consecutive hydraulic conductivities were in the range of ±25%.

Table 1. *Some geotechnical properties of the soil*

Property	**Quantitiy or Definition**
Gravel %	13
Sand %	58
Fines %	29
Soil Classification	SM
PI	Non-Plastic
Specific Gravity (Gs)	2.68
Unit weight, γ (kN/m^3)	18
Natural water content, w (%)	6.5
Void ratio, e	0.43

Figure 3. *Setup and process of the hydraulic conductivity test*

The suction measurements were done by using filter paper method (ASTM D5298-16). Filter paper method is known to be an easy, cost-effective method and the only method to measure matric and total suction together (Bulut & Leong, 2008). Filter papers were directly used from box as air dried and no pre-treatment was made. A bio-incubator type incubator (Santez SI-150K) was used during the equilibrium process and the equilibrium time was 1 week. The temperature of the incubator was held constant at 20°C with a sensitivity of ±0.1 where the relative humidity was 65%. During the matric suction measurements, the contact filter paper is buried between two soil layers. This study followed the description in Durukan and Akıncı (2017) which suggests placing the filter paper between two separately compacted soil layers in order to have a smooth contact surface between the soil layers and the filter paper. Following the suction measurements, the SWRC of the soil was also constructed by using a free program SWRC-Fit (Seki, 2007; Seki et al., 2022) and the van Genuchten parameters were determined. SWRC-Fit can fit several soil hydraulic unimodal or bimodal models to measured soil water retention data and the model of van Genuchten is one of those models.

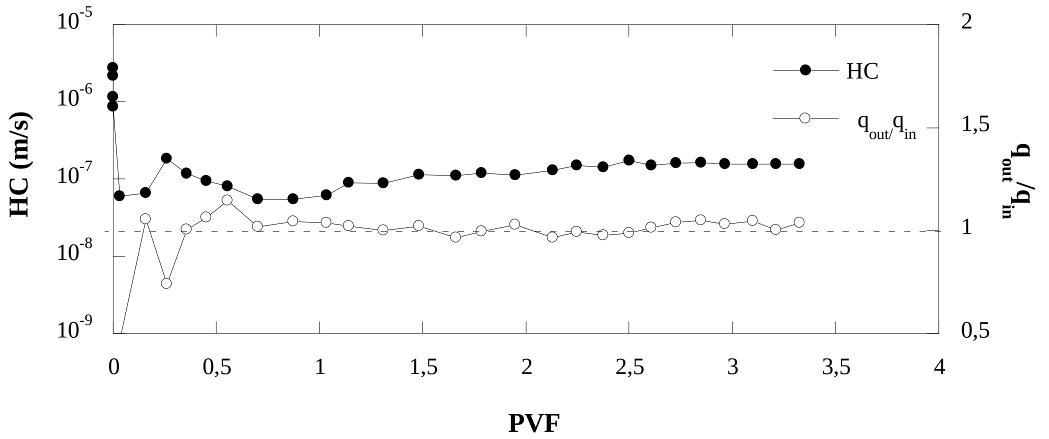
To obtain the mechanical properties of the soil, conventional direct shear tests were run for both dry and soaked conditions (ASTM D3080-11). An original soil sample was directly taken from the slope as it was in hydraulic conductivity test thus, no compaction process was needed. The box size was 60x60 mm and for soaked samples, the soil was saturated at least 24h under surcharge loading conditions. The vertical change in the specimen height was observed and when no further increase was achieved in the vertical displacement then, full saturation was also assumed to be achieved. Three tests for both dry and saturated samples were run with three different dead loading conditions and the shearing rate was 0.02 mm/min. At the end of the test, the water content of the saturated test sample was measured to be 16%. The friction angles were obtained based on the assumption of Jewell and Wroth (1987) where the horizontal plane was assumed to be the plane of maximum stress ratio (τ/σ_n)

3. RESULTS AND DISCUSSION

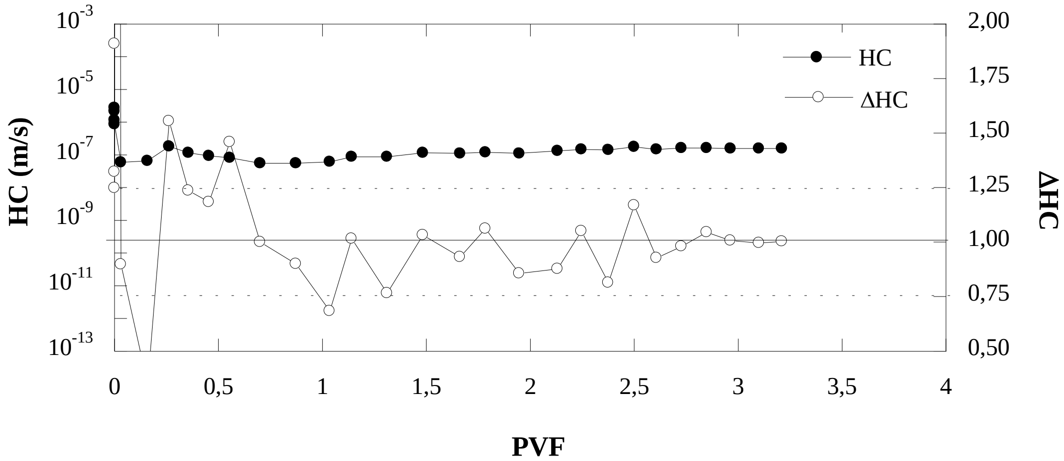
The hydromechanical properties of a soil from a slope failure were investigated. Thus, saturated hydraulic conductivity, suction characteristics and mechanical properties were determined along with basic geotechnical properties previously presented in Table 1. Hydraulic conductivity test results were presented in Figure 4 in terms of hydraulic conductivity (HC), the ratio of outlet and inlet fluid (q_{out}/q_{in}) and the change in hydraulic conductivity (ΔHC) as a function of PVF. The test lasted at least for 3 PVF and the hydraulic conductivity was found to be $1x10^{-7}$ m/s. The HC behavior of the soil sample was stable and q_{out}/q_{in} values scatter was in a narrow interval around 1 after 1 PVF (Figure 4a). Similarly, the wide scatter of ΔHC stabilized after 1.5 PVF and reached the acceptable variation limits and, after 2.6 PVF the scatter became narrower resulting in termination of the test (Figure 4b).

In order to construct a SWRC, the matric suction characteristics were detected by filter paper method. During the test there were 6 soil samples having different water contents which varied between 0 and 13%. Five of these specimens were compacted to have the same unit weight which the original sample had, for varying water contents. The 6th sample was the original air-dried sample which was also used in direct shear tests. The data was shown as dots in Figure 5 as well as the SWRC seen in dashed lines. The data showed good agreement and the coefficient of determination (R^2) was found to be 0.98. The matric suction value of the air-dried original soil sample was 2887 kPa. The suction and volumetric water content data measured from filter paper test were entered in SWRC-Fit program to obtain the van Genuchten parameters (Seki, 2007; Seki et al., 2022). The van Genuchten parameters of the soil sample which are saturated water content (cm^3/cm^3) (Θ_s), residual water content (cm^3/cm^3) (Θ_r), the soil water characteristic curve index (shape parameter of the curve) (n), a scaling parameter which is inversely proportional to mean pore diameter (cm^{-1}) (α) were presented in Table 2. These fitting parameters, n and α, are the key estimated parameters to construct a SWRC. The van Genuchten equation presenting the effective saturation (S_e) is given in Equation 3.

$$S_e = \left[\frac{1}{1+(\alpha h)^n}\right]^m \qquad and \qquad m = 1 - 1/n \tag{3}$$



(a)



(b)

Figure 4. *HC characteristics of the soil sample*
a) *along with* q_{out}/q_{in} *and* ***b)*** *along with ΔHC as a function of PVF*

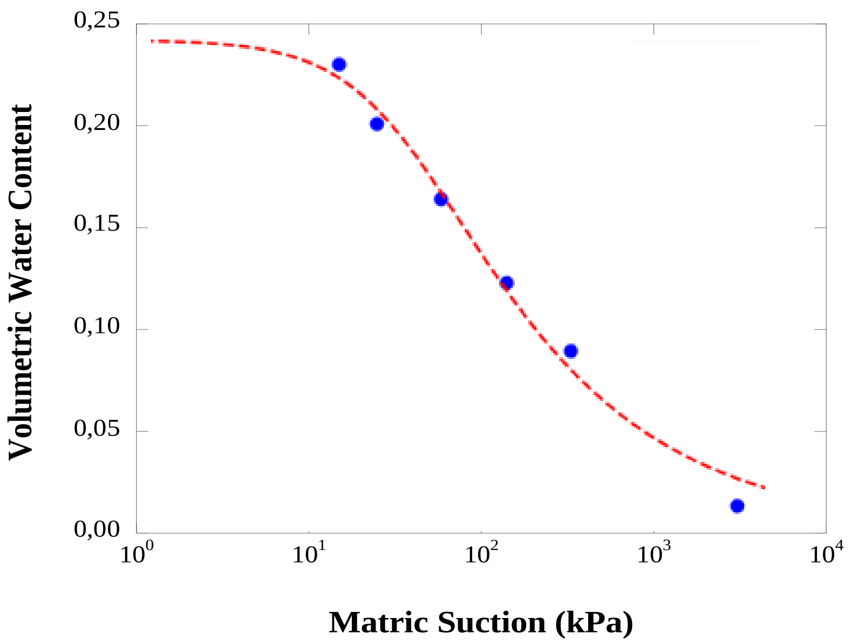


Figure 5. *SWRC of the soil sample*

Table 2. *Van Genuchten parameters of the soil*

Parameters	**Quantitiy**
Θ_s (cm^3/cm^3)	0.24474
Θ_r (cm^3/cm^3)	7.2E-16
α (cm^{-1})	0.028653
n	1.5039

Constructing a SWRC provides to obtain any suction value for a specific water content and/or saturation degree. Combining the suction characteristics with hydraulic conductivity lets one to obtain a hydraulic conductivity function (HCF). McCartney et al. (2007) investigated estimation of HCF using infiltration column tests and declared that the HCF was sensitive to any change in the moisture content and suction, which could cause inaccuracy in the gradient and also in negative pore pressures. The authors also added that the HCF predicted from the SWRC was found to underestimate the values of hydraulic conductivity. In this study, each hydraulic conductivity values (K_{Se}) were calculated using the relative hydraulic conductivity (K_r) relations defined in van Genuchten (1980) (Equation 4) related to the matric suction, saturated hydraulic conductivity, effective saturation (Se) and fitting van Genuchten parameters as mentioned in the study of van Genuchten (1980) and placed in a graph and presented in Figure 6. The hydraulic conductivity values decreased with increasing matric suction as expected.

$$K_r = S_e^{(1/2)}\left[1-\left(1-S_e^{(1/m)}\right)^m\right]^2 \tag{4}$$

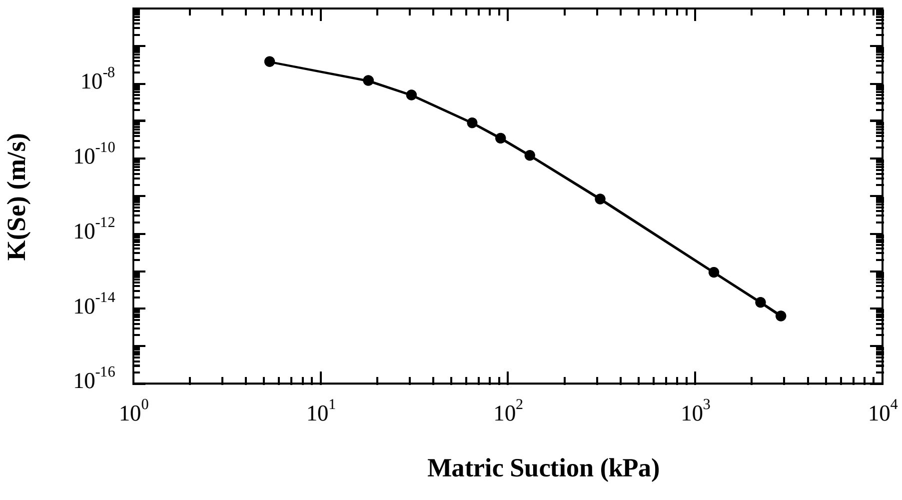


Figure 6. *The change in HC with matric suction of the soil sample*

Direct shear tests were conducted on two saturation states, dry and soaked states, and soaked state was assumed to be saturated in the study. Test results were given in Figure 7, the angle of internal friction for saturated and dry samples were 18 and 23.5 degrees, respectively. Results are in harmony with those of Bai and Liu (2012) where the angle of internal friction decreased while the water content increased. The cohesion intercepts of the dry and saturated samples were found to be 10.5 kPa and 95.5 kPa, respectively. The matric suction of the dry sample was measured as 2887 kPa. Regarding Equations 1 and 2, the friction angle due to suction, ϕ^b, referencing the change in saturated and dry states, was found as 1.7 degrees. The friction angle due to suction is expected to increase with increasing saturation and at full saturation ϕ^b to reach ϕ' as mentioned in Gan and Fredlund (1995) and Bai and Lui (2012). The shear test equipment used in this study was not modified to measure the mechanical properties for controlled suction situations so, other comparisons for ϕ^b was not done.

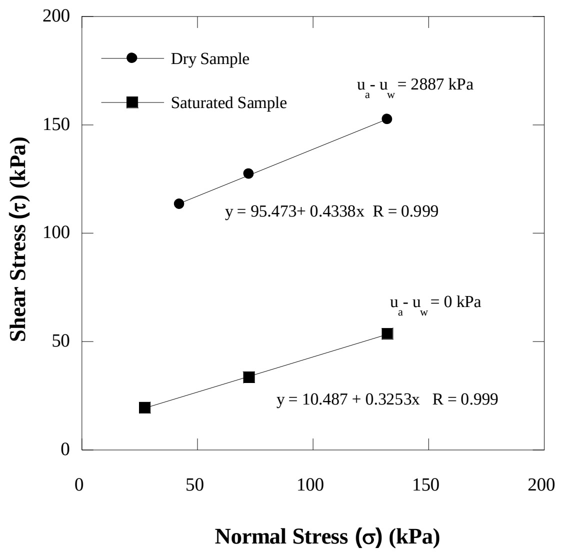


Figure 7. *Direct shear results of the soil sample*

4. CONCLUSION

The hydro-mechanical properties of a soil concerning a slope failure associated with water infiltration were investigated. In this regard, an experimental study was conducted, and hydraulic conductivity, suction characteristics and shear strength were measured along with classical geotechnical properties. Because the measured characteristics could be used in modelling the slope failure. The hydraulic conductivity and direct shear tests were done with original soil samples and saturated HC of the soil sample was found to be $1x10^{-7}$ m/s. Matric suction values were detected by filter paper method and the results gathered from suction tests were used to construct the SWRC of the soil. The maximum suction value was 2887 kPa for the air-dried original sample. Finally, the van Genuchten characteristics were found to be 0.24474 for Θ_s, 7.2E-16 for Θ_r, 0.028653 for α and 1.5039 for n. The shear strength characteristics were measured for both dry and saturated states in order to compare and calculate ϕ^b which was found to be 1.7 degrees. The angle of internal friction for saturated and dry samples were 18 and 23.5 degrees, respectively. The results were compatible with those given in literature. In addition, the cohesion intercepts of the dry and saturated samples were found to be 10.5 kPa and 95.5 kPa, respectively.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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