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Effect of Densification on the Shear Strength of Landslide Material: A Case Study from Salt Range, Pakistan

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Abstract

This research was aimed to investigate the effect of densification on the shear strength of the Simbal Landslide, which was triggered by intense rainfall in October, 2005 along the M2 Lahore Islamabad Motorway in Pakistan. Subsurface ssamples were extracted from the zone close to the basal rupture surface to allow assessment of the mobilized shear strength. Basic field and laboratory tests were conducted on remolded samples to ascertain the fundamental engineering properties of the landslide material. These included unconfined compression tests triaxial tests, and direct shear tests performed on samples of varying density and moisture content. Comparisons were made between degree of saturation and cohesion and internal friction which revealed that at low water contents the shear strength initially increases then decreases for all dry densities. This initial increase may be due to the development of apparent cohesion in the clay particles present in soil-rock mixture. The overall results suggest that the that the shear strength parameters increase with increasing dry density, and that noticeable loss of strength occurs as the soil mixture approaches saturation, independent of density.

Keywords: Landslide, shear strength, dry density, degree of saturation, densification

1. Introduction

Shear strength plays a critical role in the stability of natural and engineered slopes comprised of earthen materials (Terzaghi, 1950). The significant parameters that affect the shear strength of soil-rock mixtures include pore water pressure, percentage of gravel, relative density, normal stress, and the shape and texture of soil particles (Yazdanjou et al., 2008). Increases in pore water pressure consistently preceded loss of mobilized shear strength, likely because of reduced inter-particle friction. This tendency can trigger significant slope failures in mixtures containing materials with grain sizes < 6 mm, which either comprises the matrix or a discrete horizon dipping unfavorably (Bjerrum, 1971; Bishop, 1973).

The relationship between shear strength and pore water pressure for sandy soils have been studied by various individuals (Terzaghi 1950; Goodman and Seed 1966). Subsequent studies showed that the pore water pressure within a ground mass tends to elevate with the duration of precipitation, and is a common trigger for initiating landslides (Farooq et al., 2004; Orense et al., 2004). The relationship between shear strength, dry density and degree of saturation of soil mixtures has also been studied widely (Uno and Miyasha, 1981; Kutara & Ishizuka, 1982; Yoshida et al., 1991). These investigations revealed that as the degree of saturation increases at a particular dry density, the shear strength of the soil consistently decreases.

A consideration of these effects influenced the decision to determine in-situ densities, and to perform a range of remolded bulk density tests (Standard and Modified Proctor methods). The impact of bulk density on mobilized shear strength has long been recognized, and in granular materials significant dilation could be expected to occur along the landslide slip surface. Granular mixtures containing large boulders, gravels, and sand are abundant in the river valleys of Pakistan. These are seldom subjected to localized slope failures, unless seepage is trapped and/or focused on a particular zone or horizon. In most of the other instances in northern Pakistan, rainfall is of insufficient duration to hasten complete saturation, necessary to trigger rupture. An investigation was conducted to examine how the mobilized shear strength of the granular mixture would be affected by bulk density and moisture content.

2. Site Description and Collection of Samples

A major landslide occurred on 10th August, 2005 near the village Simbal along the Lahore-Islamabad Motorway (M-2) in the Salt Range area, after a period of intense Monsoon rainfall (Figure 1). As a result of that event approximately 91,500 m^3 colluvium and 41,000m^3 of limestone and shale boulders translated down slope and blocked one lane of the motorway (Ahmed et al., 2012).

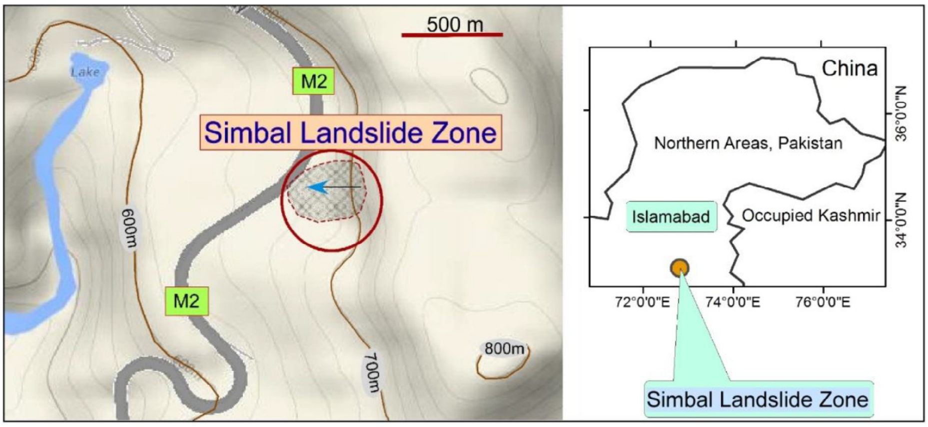

Figure 1. Location map of the Simbal Landslide, along the M2 Motorway in Salt Range Pakistan

The Simbal Landslide occurred in the Precambrian Salt Range Formation, along the leading edge of an emergent thrust sheet (Wynne, 1878; Yeasts et al., 1984; Lillie et al., 1987). The landslide activated from an area along the flank of Skaser Hill, underlain by limestone of early Eocene age (See Figure 2 A&B). The maximum thickness of the Eocene limestone in this area is about 70m (Gee 1935; Fermor 1935). There were also a number of large size boulders (> 2m) present in the landslide material, which were brought down by the landslide. Some of these boulders were observed to be embedded in the day-lighted failure surface. The landslide was approximately 75m long, 90m wide and 50m high. The pre-failure slope was inclined between 42° and 45° as observed in the field.

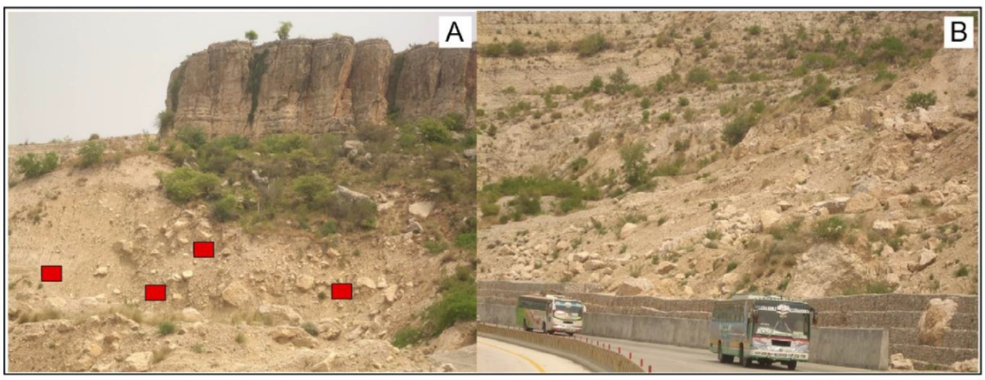

Figure 2. A) Upper part of the landslide failure surface, red squares showing the sample location on the slip surface, B) Toe of the landslide, stabilized with a retaining/gabion wall structure after failure (photographs, 2009)

Disturbed and semi-undisturbed samples were collected from the zone close to the basal rupture surface. Drive samples were taken using steel Shelby tubes, as shown in Figure 3. Five semi-undisturbed soil samples were collected at different locations along the failure surface of the landslide. Disturbed soil samples were also collected from the landslide failure surface at different locations, and these materials were mixed together transported to the laboratory to conduct a battery of remolded tests.

The in-situ dry density was determined by using the Standard Core Cutter Test method (IS- 27270, Part 29). Three is-situ samples were taken, using 152.4mm diameter core cutter molds, and the average bulk density of the matrix soil was determined (Figure 3). The average dry density of the landslide soil was found to be ~14.2 kN/m^3.

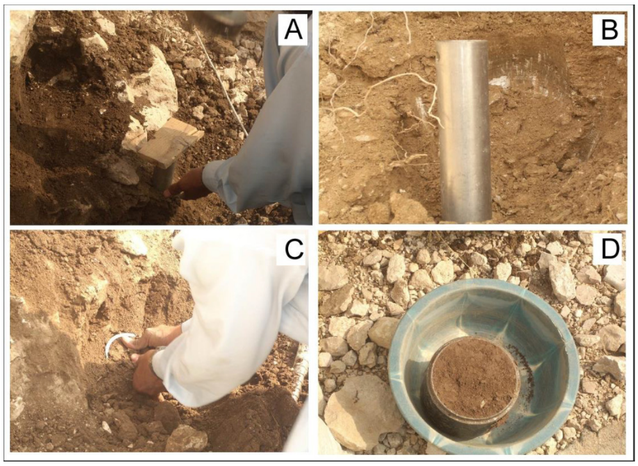

Figure 3. A & B) Soil sampling by Shelby Tube sampler, C & D) In-situ density determination by Core Cutter Method (IS- 27270, Part 29)

3. Laboratory Testing and Results

With the exception of the sieve analyses, the laboratory tests were performed on that portion of the soil samples passing the No. 4 sieve, because the field samples contained an appreciable amount of oversize material (gravel and carbonate concretions). Sieve analyses were performed in general conformance with ASTM D422-63 "Test Method for Particle-Size Analysis of Soils" (ASTM1997). Three different attempts were made to ascertain a representative gradation curve, reflective of the particle size distribution in the matrix material closest to the landslide slip surface. The average percentage of silt and clay size material in the soil matrix was 28% (Figure 4). The fraction passing No. 200 sieve fraction was evaluated using the standard hydrometer analysis test procedure provided in ASTM D4221, in order to estimate the percentage of silt and clay.

The average specific gravity of the landslide matrix was determined as 2.67, using "Standard Test method of Specific Gravity of Soil" (ASTM D854-97). This specific gravity value was used to calculate the void ratio and porosity of the soil samples and further to calculate the degree of saturation at different dry densities. The results of the Atterburg Limits tests (ASTM D4318) revealed that the liquid limit of the soil samples was 31%, the plastic limit 22%, and hence, Plasticity Index of 9, which is quite low. On the basis of the test results, the soil was classified as A-2-4(AASHTO) or GC (USCS) Silty Clayey Gravel.

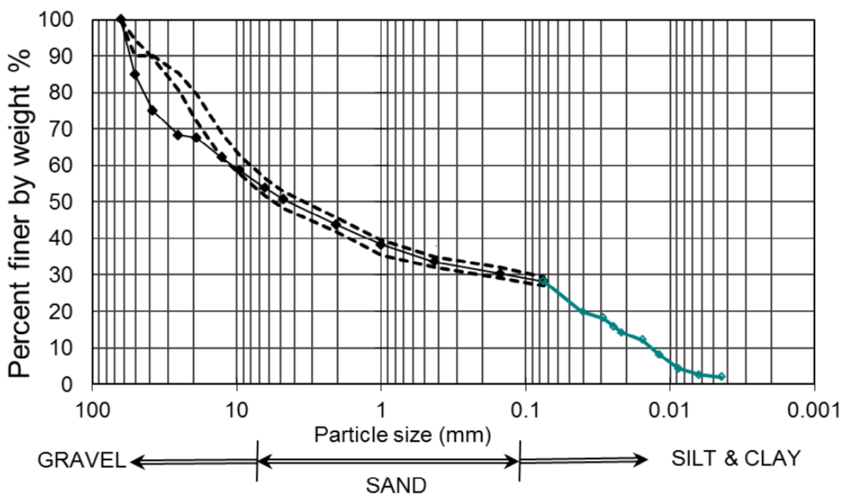

Figure 4. Gradation curve obtained from sieve analysis and hydrometer results of the soil matrix representing the Simbal landslide slip surface

The influence of dry bulk density of the soil matrix material was examined by compacting remolded samples using both the Standard Proctor method (ASTM D698-07) of 600 kN-m/m^3 and the Modified Proctor method (ASTM D1557-97) of 2,700 kN-m/m^3. These tests were performed on specimens of the landslide soil matrix to obtain the optimum moisture content and maximum dry unit weight in order to conduct a series of shear strength tests at various densities. The results of soil matrix moisture-density tests (Figure 5) showed that the maximum dry densities were 16.3kN/m^3 for the Standard Proctor and 18.5kN/m^3 Modified Proctor test, respectively. Increasing compaction density effect reduces the void sizes in the soil sample (Figure 5 and Table 1).

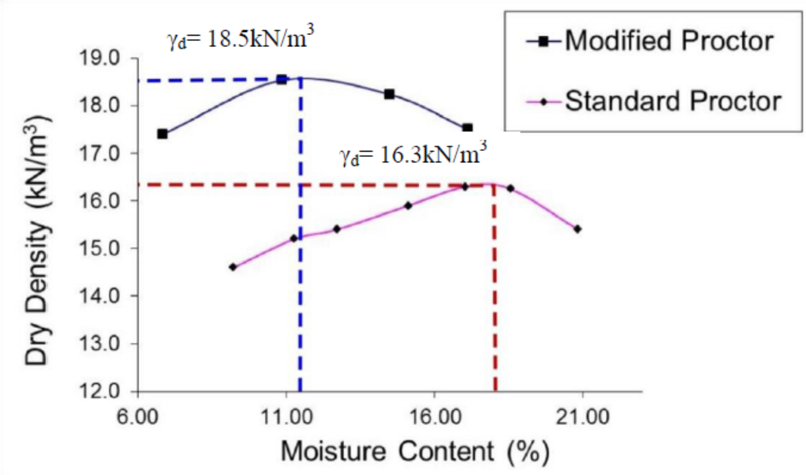

Figure 5. Soil moisture-density relationships from Standard Proctor and Modified Proctor tests

Table 1. Summary of dry density test results

Test Method	Max. Dry Density	Optimum Moisture Content OMC %
Core Cutter	γ_d= 14.2kN/m^3	14
Standard Proctor	γ_d= 16.3kN/m^3	18
Modified Proctor	γ_d= 18.5kN/m^3	11.5

The Falling Head Permeameter test (ASTM D2434) was used to evaluate hydraulic conductivity of the landslide soil matrix. This was felt to be more appropriate procedure for coarse-grained soils as well as fine-grained soils. A goal of this test was to evaluate the change in hydraulic conductivity with in-situ dry density. The purpose of this was to investigate the effect of soil densification on permeability of the soil, and later, to verify how the degree of saturation varies with soil densification.

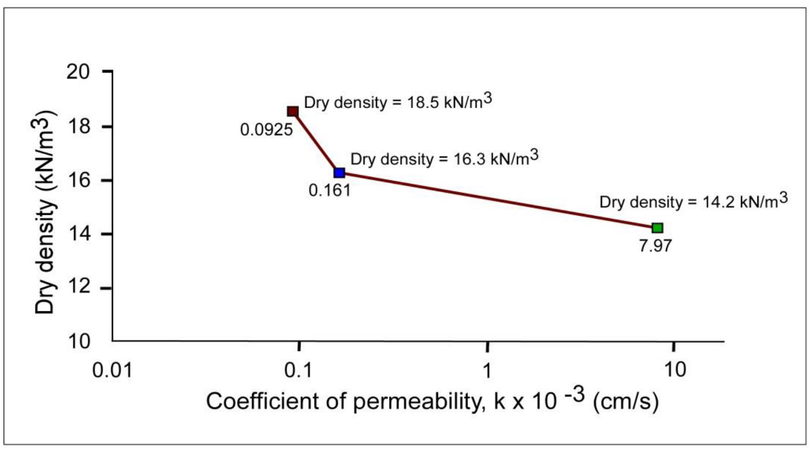

Figure 6. Variation in the coefficient of permeability with dry density of the soil matrix material

Figure 6 shows a plot of the coefficient of permeability versus dry density. It appears that the dry density of the soil increases from 14.2 kN/m^{3}to18.5 kN/m^3, the permeability decreased from 7.97x10^{-3} to 0.0925 x 10^{-3} cm/sec, respectively. This coefficient of permeability is typical of clean sand to silty sand (Freeze & Cherry, 1979). It also appears that the coefficient of the permeability drops rapidly as the density varies from 14.2 kN/m^3 to16.3 kN/m^3, and drops more slowly from16.3 kN/m^3 to18.5 kN/m^3. This shows that the soil in its natural condition is loose and fairly permeable.

Unconfined compression tests (ASTM D2166-06) were performed on semi undisturbed soil samples taken from the landslide slip surface to ascertain the compressive strength of the material. Three matrix soil samples were retrieved of the five Shelby tube samples. These were tested at their natural moisture content. The maximum load was taken to be when the sample failed or the load per unit area exceeded 20 % axial strain for the cylindrical samples, whichever is greater during the tests. Figure 7 present plots between axial stress and axial strain for the tests. The unconfined compression strengths (peak strengths before failure) were obtained as 251kPa for UDS1) and 259 kPa for UDS2).

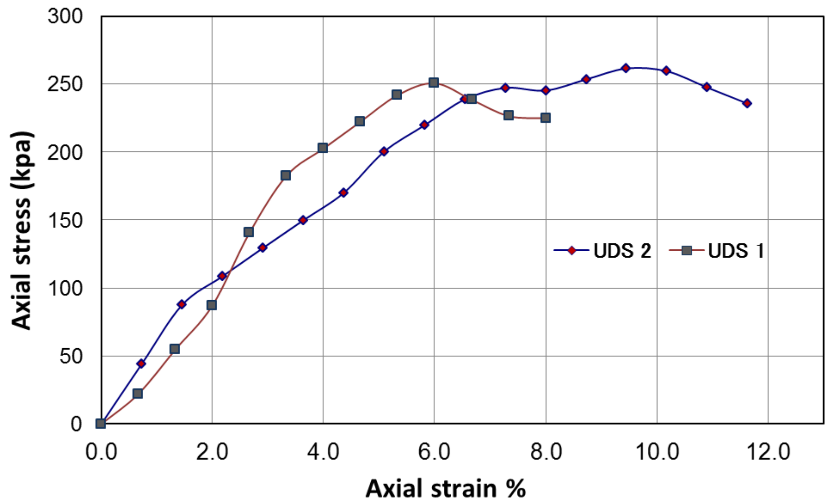

Figure 7. Stress - Strain curve to find the maximum unconfined compressive strength (UCS) of test samples

4. Shear Strength Tests and Discussion

Triaxial compression tests were carried out using the “Standard Test method for determining the shear strength of the soil (ASTM D5311-92)”. A series of unconsolidated undrained (UU) triaxial tests were performed at different degrees of saturation on samples remolded to their approximate in-situ dry density in order to study the quick response of rain water infiltration on the strength of the Simbal landside soil matrix.

To further investigate the behavior of landslide matrix material the “Standard Test method for determining the shear strength of the soil” (ASTM D3080-04) was also employed to run series of tests, varying density, moisture content, and effective stress.

4.1 Triaxial Test Results

The triaxial UU tests were performed at varying degrees of saturation (%) (i.e. 20, 30, 40, 50, 60, 70, and 88). An attempt was also made to perform triaxial test at 100% saturation, but the test was aborted. Samples up to a maximum of 88% saturation were successfully tested on the remolded samples at the in-situ dry density.

Figure 8 presents a plot between deviator stress and axial strain for each degree of saturation. The deviator stress was set at 10, 20, and 30 psi for all the tests, carried out at different degrees of saturation. A comparison of deviator stress and axial strain at varying degrees of saturation was then made in order to ascertain the effect of the degree of saturation on soil shear strength. Figure 8 also shows the shear stress-axial displacement curves for a dry density of 14.2 kN/m^3 using a constant rate of shear deformation. This plot suggests that the soil strength degrades with increasing percent of saturation, above 50 % saturation the shear strength degrades more rapidly. Figure 9 presents Mohr’s circle plot for the case of 20% saturation, with an in-situ density of 14.2kN/m3. The density of the various samples was held constant for all of the triaxial tests. Friction angles and cohesion intercepts were obtained by inspection of similar plots for each increment of saturation, from 30% to 88%. Table

2 presents a summary of the triaxial test results. The specimen cohesion intercept decreased from 42.4 kPa (at 40% saturation) to 5.5 kPa (at 88% saturation); while the angle of internal friction decreased from 35.4° (at 30% saturation) to just 4° (at 88% saturation). Figures 10 present the variation of cohesion and friction with percent saturation. Note that the cohesion rises markedly from 20 to 40% partial saturation, and then decreases linearly with increasing levels of partial saturations; the Figure 10 further illustrates how the inter-particle friction decreases almost linearly with increasing moisture content.

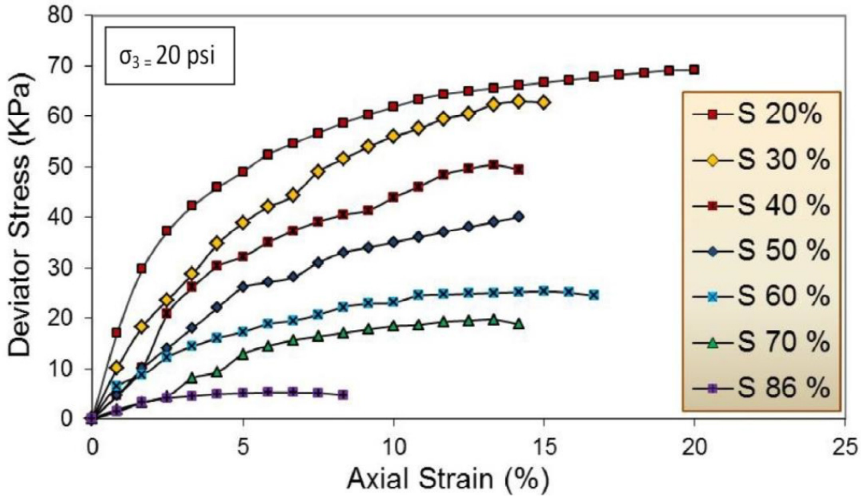

Figure 8. Relationships between deviator stress and axial strain at varying degrees of saturation on samples remolded to the in-situ field density

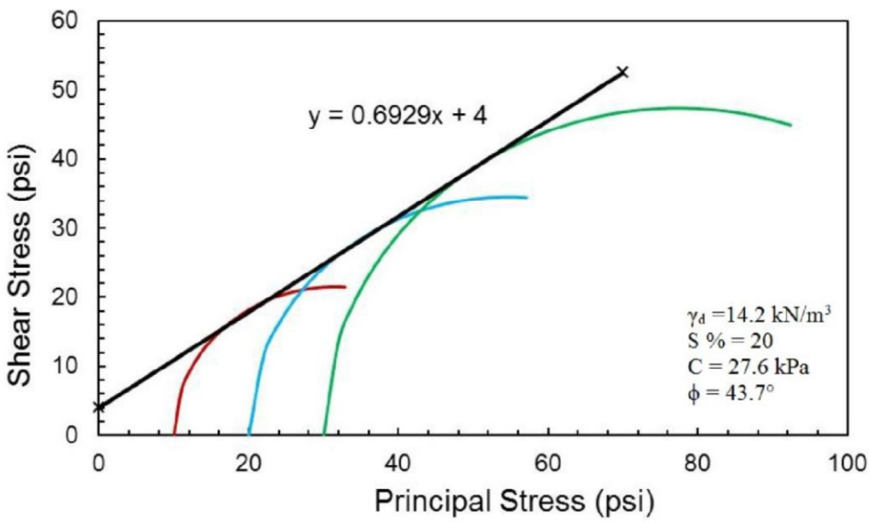

Figure 9. Failure envelopes for Simbal landslide matrix for different normal stresses with a remolded dry density of 14.2kN/m^3

Table 2**.** UU triaxial test results, comparison of cohesion and friction angle with the varying degrees of saturation

Deg. of Saturation (%)	ϕ (Degrees)	Cohesion(kPa)
20	34.7	27.6
30	35.4	34.3
40	24.5	42.4
50	21.3	40
60	15.2	24.8
70	12.4	24.1
88	4	5.5

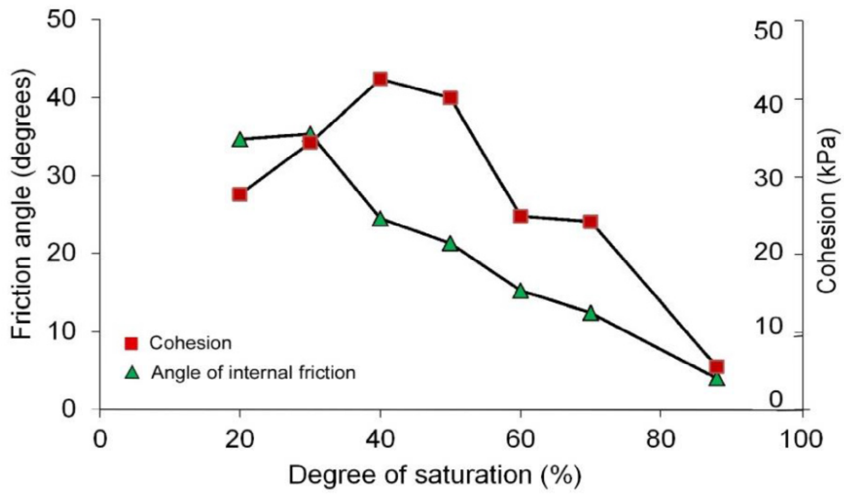

Figure 10. Relationship between friction angle, apparent cohesion and degree of saturation % at natural dry density (γ_d =14.2 kN/m^3)

The Simbal landslide matrix material contained coarse particles and small carbonate concretions, so direct shear test were performed to investigate the relative contributions of shear strength parameters controlling the landslide matrix. The "Standard Test method for determining the shear strength of the soil" (ASTM D3080-04) was employed to run more than 100 tests, varying density, moisture content, and effective stress. The dimensions of the direct shear machine box was 6 x 6 x 2 cm. Remolded samples were prepared for direct shear testing and the moisture content was so adjusted for each sample to obtain the desired degree of saturation.

4.2 Direct Shear Test Results

In order to examine the relationship of shear stress with increasing deflection (a proxy for shear strain), tests were conducted using normal loads of 84N (= σ_n 23 kPa), 129N (= σ_n 36 kPa), and 173N (= σ_n 48 kPa), while varying the percent saturation from 20 to 100% (Ahmed et al., 2012). A series of plots were constructed, illustrating how shear stress varies with increasing strain for the three normal loads and increasing degree of saturation. All these tests were performed on remolded samples with varying degrees of saturation at different densities. The goal of these tests was to plot the load deformation curves at different densities to ascertain the maximum shear strength values with their respective maximum horizontal deflections.

Figure 11 shows the relationship between shear stress and horizontal deflection for normal loads of 129N with increasing saturation, at in-situ dry density. The maximum shear stress was determined for each case and plotted against respective normal loads, in order to find out the shear strength parameters (c and ϕ).

Figure 12 illustrates the observed relationship between mobilized shear and normal stresses, with increasing percent saturation. The slope of these lines appears to approximate the angle of internal friction, while the y-axis intercepts approximate the apparent cohesion of the matrix soil, illustrating how these strength parameters vary with the degree of saturation. The results suggest an apparent inverse relationship between mobilized shear strength and percent saturation, which are consistent with results cited in studies examining the impact of partial saturation on embankment deformation (Noorany et al. 1992; Rogers 1992). The apparent cohesion intercept (c) of the soil matrix material dropped from 18.4kPa to 5 kPa, while the inferred angle of internal friction, (ϕ) decreased markedly, from 29° to 8.5° as the degree of saturation increased from 20 to 100 %. An investigation by Miyashita (1981) found that cohesion decreased as the percent saturation increased in sandy soils. For inorganic soils containing a high percentage of fines, they observed that the shear strength parameters (c and ϕ) decreased with increasing percent saturation.

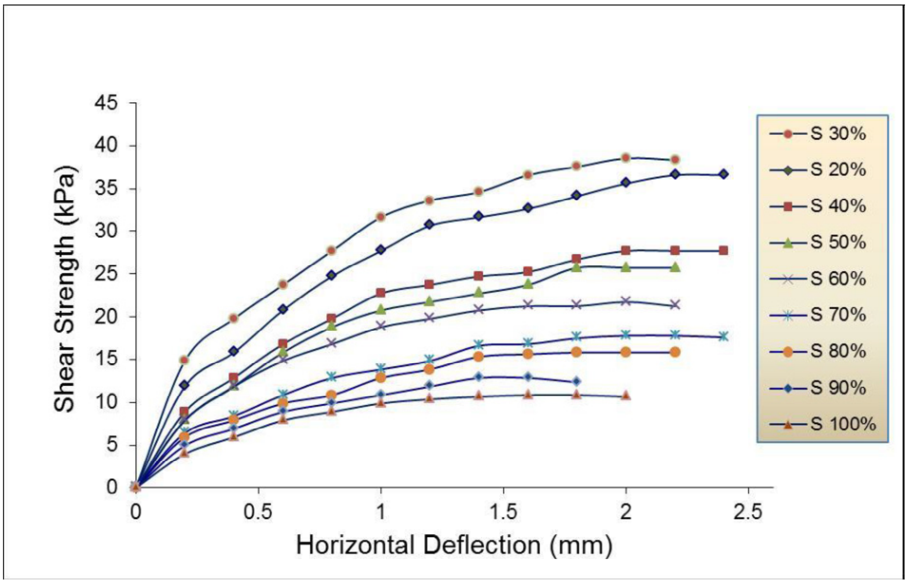

Figure 11. Variation of mobilized shear stress versus horizontal deflection (σ_n= 36 kPa) at in-situ dry density (γ_d =14.2 kN/m^3) in direct shear tests conducted on the landslide matrix soil

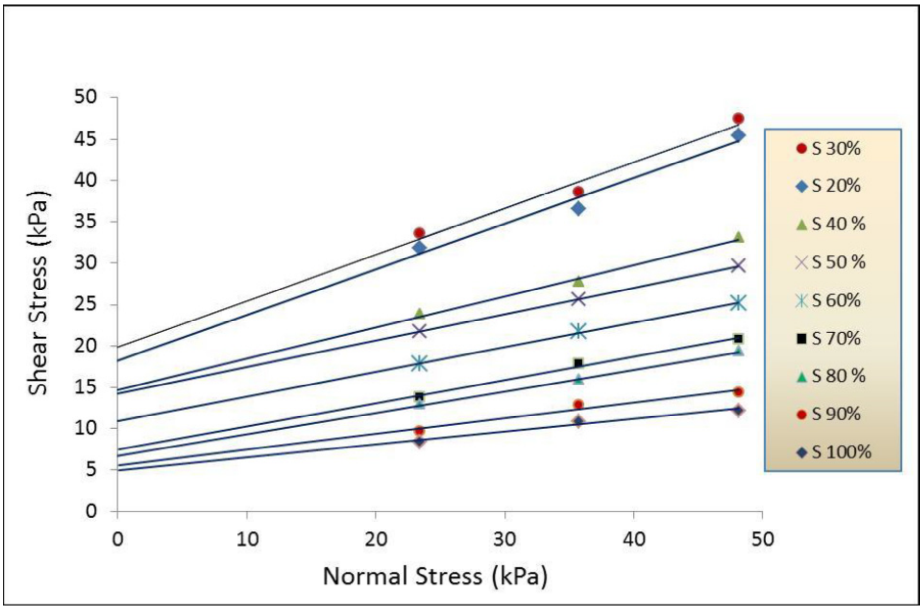

Figure 12. Observed relationship between shear and normal stress at the in-situ (natural) dry density (γ_d =14.2 kN/m^3)

The shear strength parameters "c and ϕ" were obtained from direct shear strength tests on remolded samples of the landslide's matrix soil (that portion finer than the No. 4 sieve). The actual slide debris contained coarse materials, including boulders with diameters as great as 5m. The mobilized shear strength parameters of the coarse landslide material could be expected to be slightly less than those obtained from laboratory testing (Marachi, et al., 1972).

The same methodology described above was followed while conducting the balance of the direct shear tests, but varying the dry density (Standard and Modified Proctor). Similar trends were noted, comparing shear stress versus horizontal deflection (Figures 13 and 15), and shear stress versus normal stress (Figures 14 and 16) at varying degrees of saturation. The variation in the shear strength parameters, c and ϕ were observed which vary from 24.7 kPa to 6.9 kPa and friction angles 32.6° to13° respectively for standard Proctor dry density. For the Modified Proctor density, these parameters vary from 25.7 kPa to 7.9 KPa with friction angles of 35.8° to 14.1°.

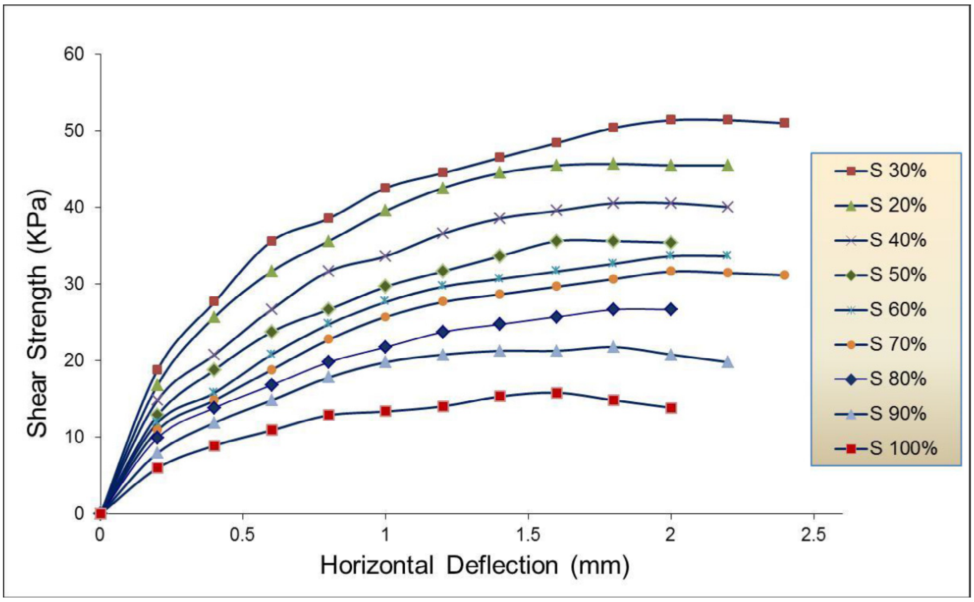

Figure 13. Results of direct shear tests, between shear stress and horizontal deformation (σ_n = 36 kPa) at Standard Proctor dry densities (γ_d =16.3 kN/m^3)

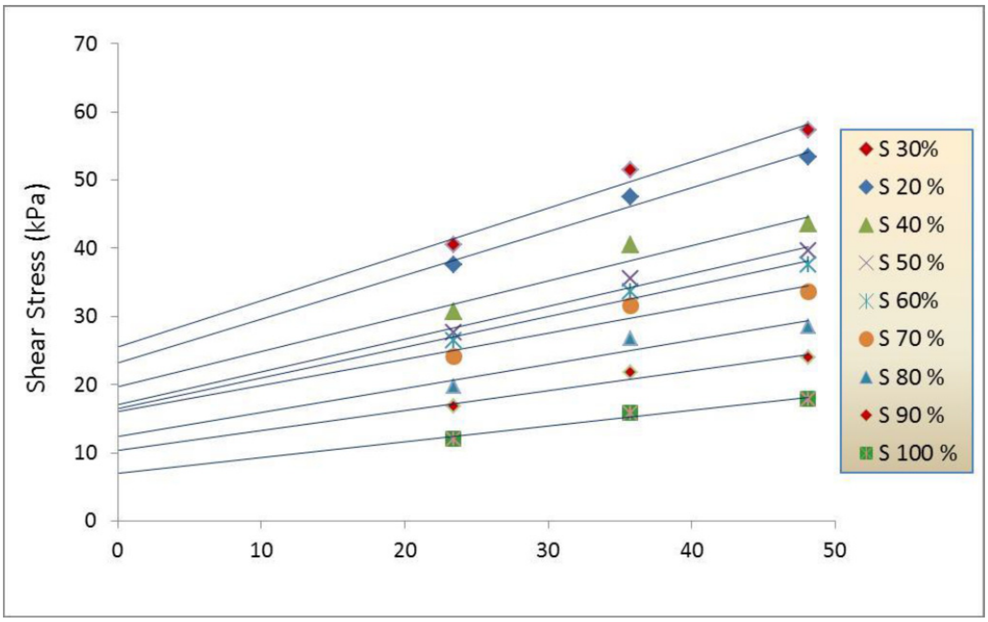

Figure 14. Plots of shear versus normal stress in the direct shear tests, illustrating fairly linear relationships at Standard Proctor dry densities (γ_d =16.3 kN/m^3)

Figures 17 and 18 illustrate the role of compaction on the material behavior. By increasing the specimen's density, the overall rigidity of the specimens (initial slopes of the curves) increases. Figure 18 compares degree of saturation with cohesion at different densities. Figure 18 compares the angle of internal friction with degree of saturation at different densities. The investigation sought to evaluate how the shear strength of samples can be improved through densification. The direct shear test results conducted at different densities consistently showed a noticeable correlation between soil density and shear strength parameters. The results indicate that there is a linear increase the shear strength with increase in the density of the Simbal landslide matrix material.

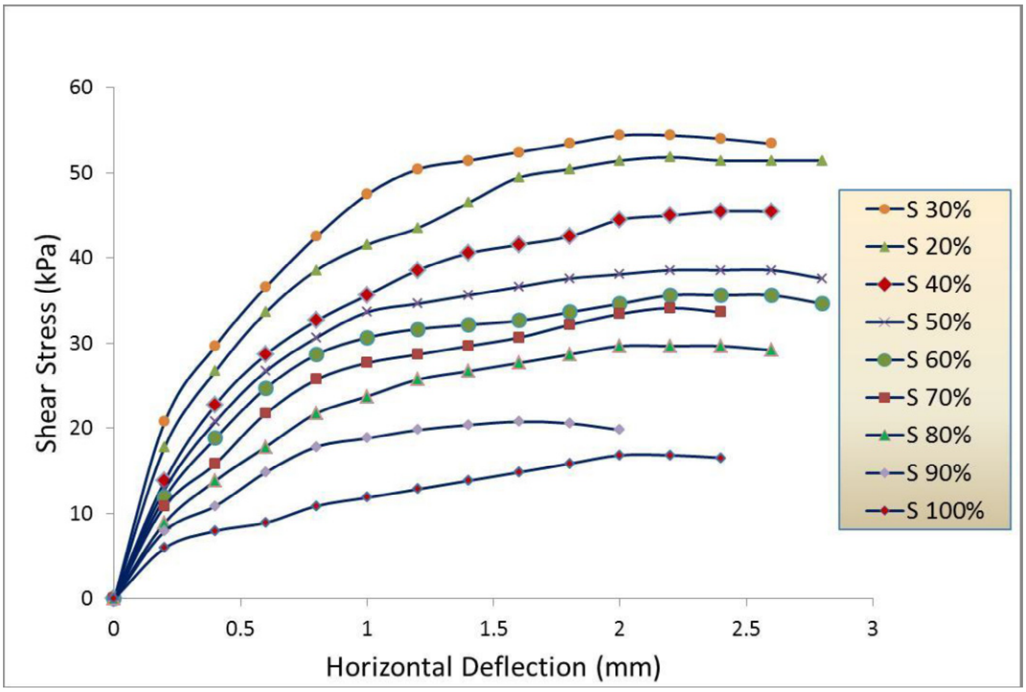

Figure 15. Plots of the shear stress versus shear displacement (at σ_n= 36 kPa) for varying degrees of saturation and constant rate of shearing at Modified Proctor densities (γ_d =18.5 kN/m^3)

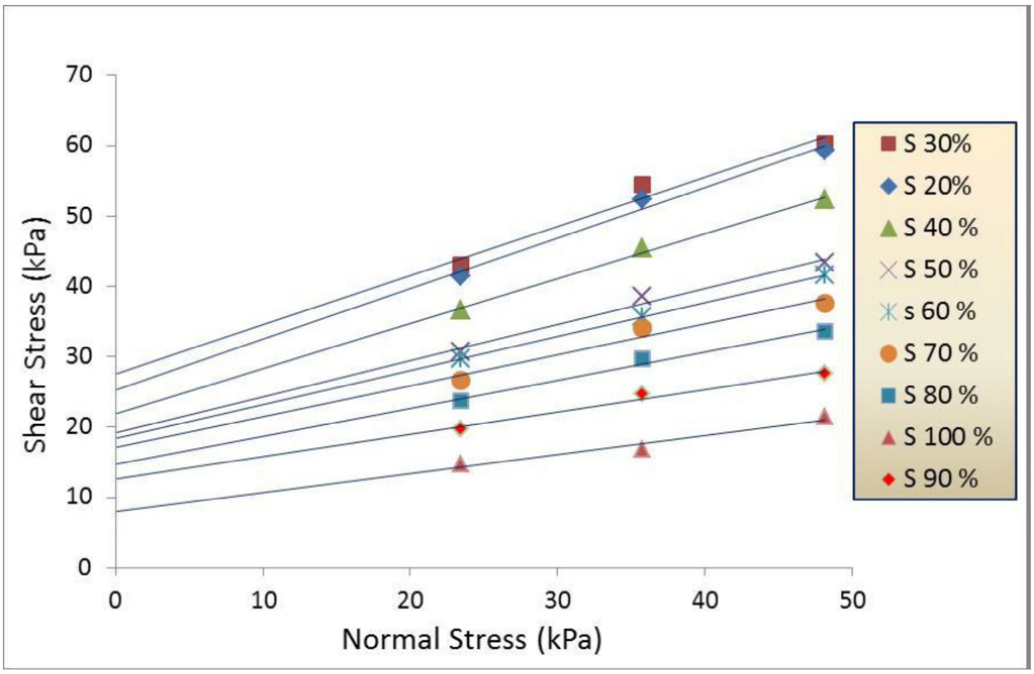

Figure 16. Relationship between shear stress and normal stress at Modified Proctor dry densities (γ_d =18.5 kN/m^3)

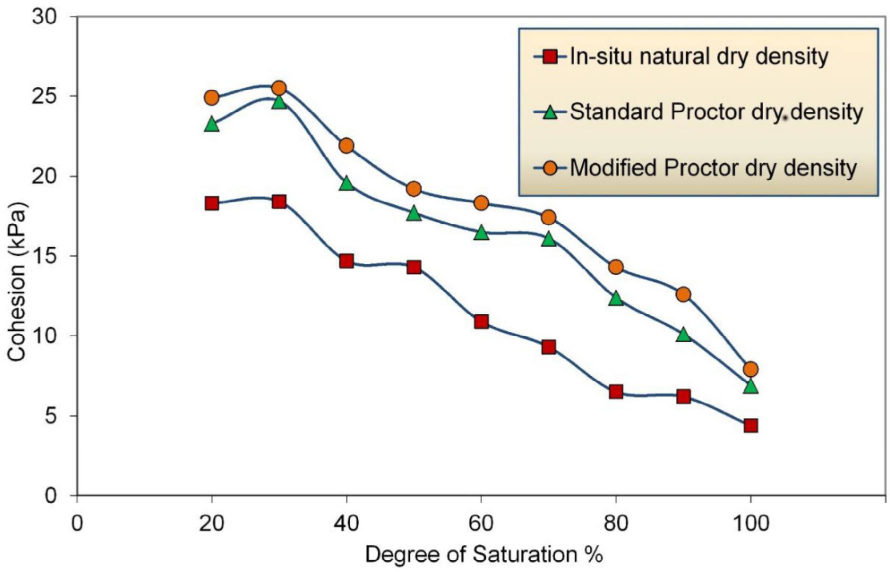

Figure 17. Variation in apparent cohesion of the soil matrix at different dry densities at varying degrees of saturation

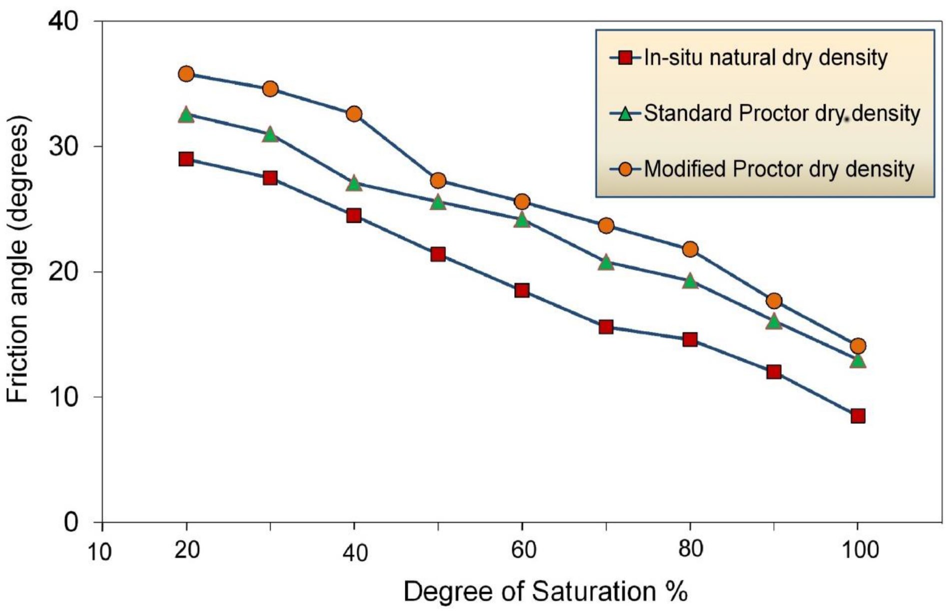

Figure 18. Variation of friction angle of the soil matrix at different dry densities at varying degrees of saturation

From 20% to 30% saturation the apparent cohesion improved slightly, but decreases with increasing degree of saturation above this threshold. This aberration might be ascribable to soil water tension, engendered by the meniscus of capillary water. These data showed a consistent decrease in matrix soil friction with increasing degree of saturation, as would be expected. The tests results were consistent in demonstrating the impact of increased matrix soil density on the shear strength parameters, and the corresponding decrease of mobilized shear strength with increasing degree of saturation. The impact of bulk density on mobilized shear strength of the landslide's matrix soil material was also probed. The shear strength was consistently improved by increasing density, but decreased with increasing percent saturation, in every case.

5. Conclusions

A comprehensive program of geotechnical testing procedure was carried out to ascertain the basic engineering properties, shear strength parameters, and effect of densification on the mobilized shear strength of the Simbal landslide material, assuming a constant rate of shear displacement. Shear strength parameters were explored using unconfined compression tests, triaxial tests, and direct shear tests on remolded soil samples at different dry densities.

The triaxial tests were carried out at cell pressures of 10, 20 and 30 psi with constant rates of shear. The results showed a decrease in shear strength parameters with increasing degree of saturation at in-situ densities (see Figure 10).The effect of compaction densities (14.2kN/m^3, 16.3kN/m^3 and 18.50 kN/m^3) on samples of varying degrees of saturation were also investigated, at a constant shearing rate in a series of direct shear tests. Normal stresses of 23 kPa, 36 kPa and 48 kPa were used for the direct shear tests. Peak strength values were achieved early (at low strain rate) in the samples tested at in-situ dry density, but sample prepared at the Standard and Modified Proctor densities exhibited denser packing, which tended to improve their mobilized shear strength parameters (c and ϕ). The shear strength parameters consistently dropped with increasing degree of saturation (See Figure 17&18).

This research has some limitations associated with sample preparation and testing equipment. Laboratory tests on in situ materials using large shear boxes are recommended to obtain a more realistic picture of the effect of strain rate on shear strength of coarse blocky material.

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