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# Stability of Undisturbed Residual Soil Hill Slopes

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**ABSTRACT:** The cut slopes of saprolitic residual soils in the Himalayan foothills often remain stable at very steep inclinations that are much steeper than critical failure slope angles predicted by stability analysis. It is often difficult to obtain undisturbed samples of these soils. Physical inspection shows natural weak cementing property of undisturbed saprolitic residual soil. In order to overcome the inability of standard sampling techniques to collect undisturbed samples of the fragile saprolitic residual soil from the hillslope surface, a procedure with a modified sampler is adopted in this research. The shear parameters of undisturbed samples thus collected as well as that of reconstituted samples of the same soil are determined in direct shear testing at different saturation levels. Stability analysis of the saprolitic residual soil hill slopes was carried out using both undisturbed and remoulded soil properties at different degrees of saturation which revealed a positive contribution of the cementing property of the undisturbed soil towards higher stability of hill cut slopes.

**KEYWORDS:** Saprolitic residual soil, Undisturbed sample, Shear parameters, Slope stability.

## 1. INTRODUCTION

Residual soil, formed from weathering of parent rocks, is a predominant geological formation constituting the slopes of Himalayan foothill region. The hill cut slopes in these soils frequently experience localized shallow landslides resulting in loss of life and property in addition to obstruction to road and rail traffic. Due to the climatic condition in the Himalayan foothill, these residual soil slopes are in unsaturated condition during winter and their failures are often triggered by rainfall during monsoon. Several studies have been directed towards the effect of rainfall on the stability of cut slopes in these hill soils (Rahardjo et al., 2007; Gofar and Lee, 2008; Huat et al., 2008; Ling and Ling, 2012). The laboratory testing of unsaturated soil and the subsequent theoretical formulations and solutions is tedious and technically challenging, compared to saturated soil (Fredlund, 2006). The shear strength of these soils is influenced by the degree of decomposition and bonds between the micro particles of the residual soil (Meng and Chu, 2011). Investigations have been carried out to research for determination of shear parameters of unsaturated soil considering the stress state variables, net normal stress and matric suction (Satija, 1978; Escario and Sàez, 1986; Toll, 1990; Fedlund and Rahardjo, 1994; Gan and Fredlund, 1996; Khalili and Khabbaz, 2001; Toll and Ong, 2003; Houston et al., 2008; Chen et al., 2009; Das and Saikia, 2010; Jotisankasa and Mairaing, 2010; Guan et al., 2010). Due to significant difficulty in sampling and testing with a very low recovery chance of undisturbed samples (Klein and Trimble, 2008), investigators have used reconstituted samples to determine the shear parameters. Only a few studies have included testing of shear behaviour of undisturbed residual soil samples (Ho and Fredlund, 1982; Rahardjo et al., 1995; Klein and Trimble, 2008; Jotisankasa and Mairaing, 2010; Alonso and Gens, 2011; Saffari et al., 2019). Most of these studies used thin walled samplers to extract undisturbed samples from SPT bore holes. Samples were also dug out in large sized blocks, especially from the surface or shallow depth ground surfaces (Raihan Taha et al., 1998; Huat et al., 2005; Klein and Trimble, 2008; Rahman et al., 2018). From the block samples, test size samples for triaxial or direct shear tests were carefully cut out but with very limited success due to the extreme brittleness of the soil. But no comparison of strength parameters obtained using undisturbed and reconstituted samples of residual soil has been carried out in the published literature.

Physical examination of the undisturbed saprolitic residual soil indicated the existence of weak cementing property, which is not noticeable in reconstituted samples prepared using the same soil. As it is often difficult to obtain undisturbed samples of these soils, most shear strength parameters used in the stability analysis are derived either from laboratory testing of remoulded samples or from experience or correlations with index parameters (Klein and Trimble, 2008). It is possible that the shear properties of the saprolitic residual soil obtained from reconstituted samples give conservative values due to the absence of this cementing property in it. This may be a reason for the field observation that cut slopes in saprolitic residual soils remain stable at slope inclination much steeper than the critical failure slope angles predicted based on reconstituted strength parameters of the soils reported. In an attempt to bridge this gap between theoretical prediction and actual field observation, this study focuses on careful experimentation preserving the cementing property of the undisturbed saprolitic residual soil in the determination of shear properties and stability analysis of hill slopes in these soils.

## 2. INVESTIGATION METHODOLOGY

### 2.1 Collection of Representative Samples

The study area is located at 26.10000 N Latitude and 91.86670 E Longitude in the hilly terrain of North Eastern part of India. The hill surface sub-soil was exposed due to ongoing hill cutting for road construction. Furthermore, the samples were collected from the exposed hill cut slope to determine physical properties and classify the saprolitic residual soil. The physical and index properties of the soil are summarized in Table 1.

Table 1 Index properties of the saprolitic residual soil

| **Soil property** | **Values from laboratory tests** |
|---|---|
| Specific gravity | 2.63 |
| In situ bulk density (g/cc) | 1.60 |
| In situ water content(%) | 2.20 |
| In situ voids ratio | 0.642 |
| Permeability (m/s) | $1.40 \times 10^{-6}$ |
| Fines content (%) | 7.6 |
| Liquid Limit (%) | 35 |
| Plastic limit (%) | No plastic |
| Co-efficient of uniformity ($C_U$) | 5.16 |
| Co-efficient of curvature ($C_C$) | 1.43 |
| Classification as per the Unified Soil Classification System (USCS) | SP-SM (Poorly graded silty sand) |

Visual examination of the soil reveals that it carries the texture of the parent rock and appears to have good strength in intact field condition. But when sampling is attempted, its microstructure is found to be highly brittle. Collection and subsequent extraction of intact samples using core cutter or even thin samplers were found to be very difficult, almost impossible. Cutting samples of suitable size for direct shear tests from block samples was unsuccessful as the samples broke to pieces. It is perhaps due to this difficulty in collecting undisturbed samples of this saprolitic residual soil using common samplers. There is very little study on the strength and stability of these residual soil slopes based on undisturbed strength parameters in published literature. In this study, therefore, a modified procedure is devised to collect undisturbed samples of the residual soil to determine its strength parameters in the laboratory.

## 2.2 Sampling and Test Procedure

Undisturbed block samples were first obtained from the freshly exposed surface of the hill slope. In order to extract the block sample without disturbing the fragile soil structure, a sampling box was made using galvanize iron (GI) sheets of thickness 0.28 mm. This was a modification of the 2.5 mm thick 60 mm x 60 mm sampler normally used in direct shear test, which was too thick to keep the fragile saprolitic residual soil undisturbed. The size of the modified square-shaped box was 100 mm x 100 mm with 60 mm depth, as detailed in Figure 1. One of the box's 100 mm x 100 mm faces acted as the base of the sampler, while the other square face was kept open for sample insertion. The side faces were rigidly connected to the four edges of the square base to strengthen them against buckling during the sample collection process. One of the side faces was kept openable by a sliding mechanism to facilitate the extraction of samples from the box in the laboratory.

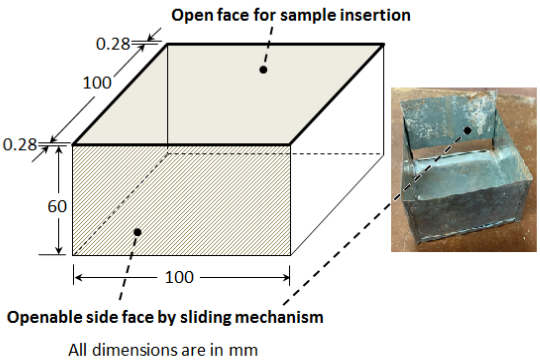



Figure 1 Details of the modified sampler box

To collect block samples, a suitable location of freshly exposed face of hill cut slope was selected, and the face was made plane and smooth by scrapping with trowel. The open face of the GI sheet sampler box was evenly inserted into the soil, pushing with both hands to the possible extent, as shown in Figure 2(a). It was then pushed further into the soil up to the full depth of the sampler box by applying blows with a wooden hammer on the back of the base. During the hammer strike, the back of the GI base was covered with a 40 mm thick wooden board to ensure uniform penetration of the sampler and minimum disturbance to the sample soil. Once the sampler was fully penetrated into the slope soil, it was dug out carefully from the slope soil by scrapping out the surrounding soil.

(a) (b)

Figure 2 Collection of soil sample using the modified sampler: (a) Driving of sampler into soil and (b) Extracted sample with sampler

The exposed surface of each extracted soil sample was visually inspected, and only the samples showing intact structure were accepted for laboratory testing. The extracted sample and the sampler are shown in Figure 2(b).

For transportation to the laboratory, the samples in sampler boxes were carefully placed in metal trays. The space surrounding the samplers is packed with the same type of soil so that there is no lateral movement of the samplers during transportation. The trays are placed on a soft jute cushion to reduce vibration during transportation. Intact soil lumps were separately collected from the same location and sealed in plastic bags for determination of index properties in laboratory.

Laboratory undisturbed samples were extracted for direct shear testing from the block samples collected from the field in the sampler boxes. A sampler of size 60 mm x 60 mm x 30 mm was made from a 0.28 mm thick GI sheet with the top and bottom square faces open for the direct shear test sample extraction. This smaller sampler was carefully inserted into the undisturbed sample collected from the field by uniformly pressing its all four faces from top and simultaneously scrapping out the soil from its outer periphery with a sharp edge, taking care not to disturb the soil inside the sampler while scrapping as shown in Figure 3. The soil scrapped out from the outer side of the smaller sampler was stored in plastic bags to prepare the remoulded samples.

Figure 3 Extraction of undisturbed sample for direct shear test

After extraction of the test sample in the smaller sampler the top and bottom open faces of the soil sample were covered with two grooved metal plates of standard direct shear box apparatus. The GI sampler was then carefully removed by slightly opening up its side faces. The sample and the metal plates were then transferred into the direct shear box. While transferring the sample into the direct shear box placing the sample inside the box from the top was not feasible without disturbing the sample soil microstructure. So the sample, supported by the metal plates, was placed on top of a wooden block of size 45 mm x 45 mm x 100 mm (height). The shear box was taken out of the direct shear equipment and was very carefully placed inverted on the sample while maintaining the vertical alignment. The shear box and the sample were then made erect again by holding in place the metal plate supporting the sample and the assembly was placed in the direct shear testing apparatus.

The scrapped out soil from the outer side of the smaller sampler, which was stored in plastic bags, was used to prepare the remoulded samples. The remoulded specimens were prepared by weighing the calculated quantity of soil to achieve the same dry density as that of undisturbed specimen and tamping in three equal layers inside the shear box to a thickness of 30 mm.

## 2.3 Direct Shear Test

Direct shear test was carried out following the procedure laid down in BIS code No. 2720 (Part 13) – 1986. 60 mm x 60 mm shear box was used in the test, and the specimen width to thickness ratio of 2:1 was maintained for both undisturbed and disturbed soil samples. In order to study the effect of saturation on shear strength of the saprolitic residual soil, the shear tests were conducted at five different saturation levels of the soil, as shown in Table 2.

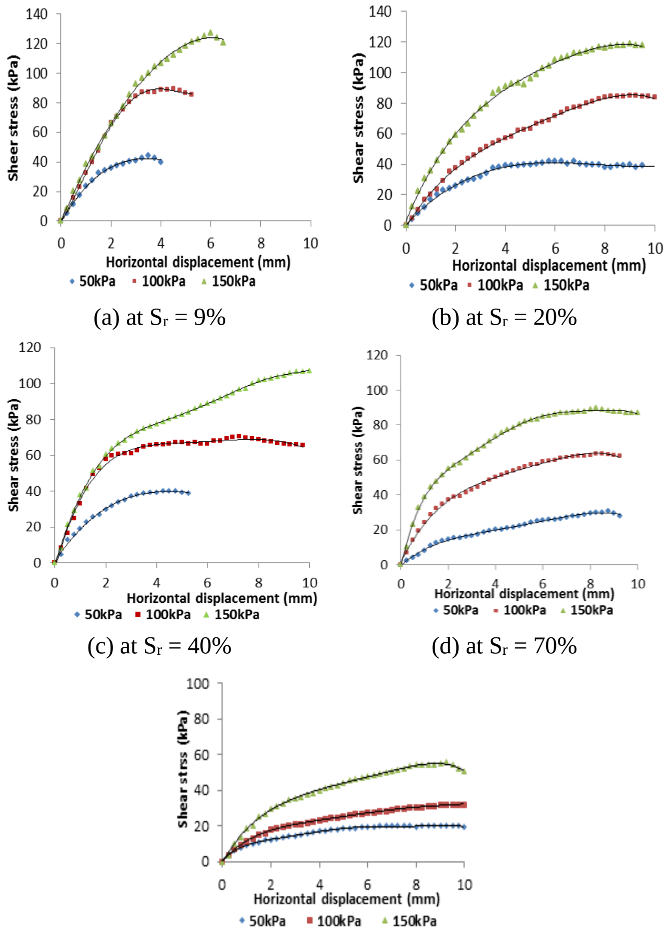
The required amount of water was theoretically computed from the target water content as in Table 2, and it was added slowly in drops using a syringe to the top surface of the sample in direct shear box. Care was taken to avoid water flooding on top of the sample during this process. The wetted sample and the shear box were then wrapped in plastic bag and placed inside dessicator for 24 hours for uniform distribution of the water throughout the sample. Trial tests were carried out to check the sufficiency of the procedure by measuring the water content of the trail samples after 24 hours. It was found that the theoretically computed quantity of water needed to be increased by 15% to achieve the target water content. It was also noted that there was a maximum 3% variation in water content at different depths within the same sample for low water content (<10%) samples. There was a negligible water content variation within a sample for the higher water content samples. Strain rate of 0.25 mm/min was maintained in all the tests.

Table 2 Degrees of saturation of samples tested in Direct Shear Test

| Degree of Saturation, $S_r$% | 9% | 20% | 40% | 70% | 95% |
|---|---|---|---|---|---|
| Water content, w% | 2.20 (in-situ) | 4.88 | 9.76 | 17.09 | 23.20 |

## 3. RESULTS

The shear stress vs. horizontal displacement curves for degree of saturation ($S_r$) = 9%, 20%, 40% and 70% obtained from the direct shear tests of the undisturbed soil samples are shown in Figure 4. The tests were conducted for normal stress 50 kPa, 100 kPa, and 150 kPa.



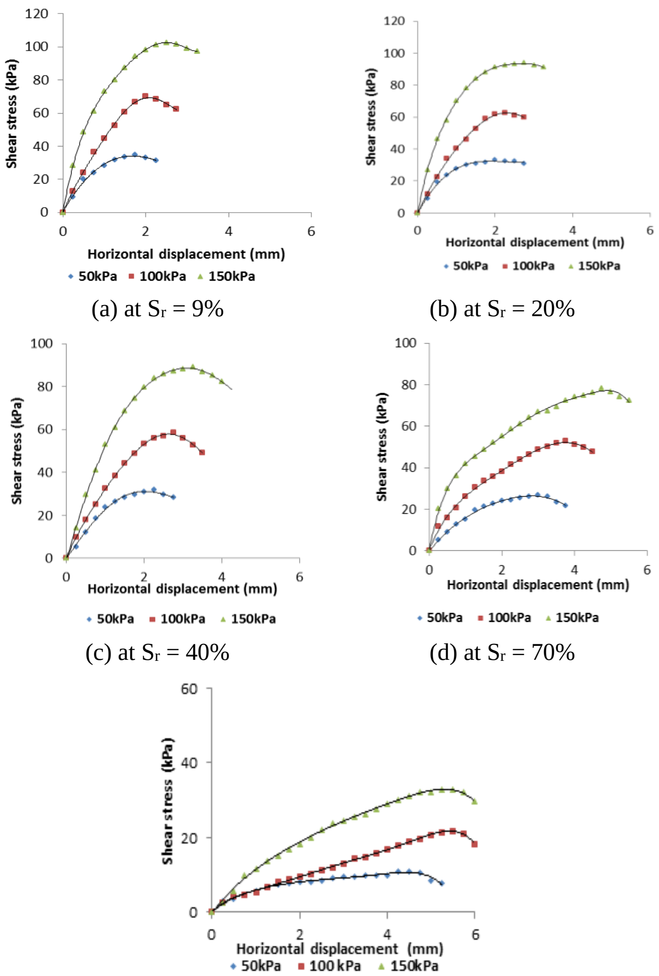

(a) at $S_r$ = 9% (b) at $S_r$ = 20%

(c) at $S_r$ = 40% (d) at $S_r$ = 70%

(e) at $S_r$ = 95%

Figure 4 Results of direct shear tests on undisturbed samples under normal stress 50 kPa, 100 kPa, and 150 kPa

The shear stress vs. horizontal displacement curves for Sr = 9%, 20%, 40%, and 70% obtained from the direct shear tests of the reconstituted soil samples are shown in Figure 5. The tests were conducted for normal stress 50 kPa, 100 kPa and 150 kPa.




(a) at $S_r$ = 9% (b) at $S_r$ = 20%

(c) at $S_r$ = 40% (d) at $S_r$ = 70%

(e) at $S_r$ = 95%

Figure 5 Results of direct shear tests on reconstituted samples under normal stress 50 kPa, 100 kPa, and 150 kPa

The shear strength parameters, cohesion (c), and angle of friction (φ) of the undisturbed and remoulded samples are determined from the failure envelopes of the respective direct shear test results and are presented in Table 3.

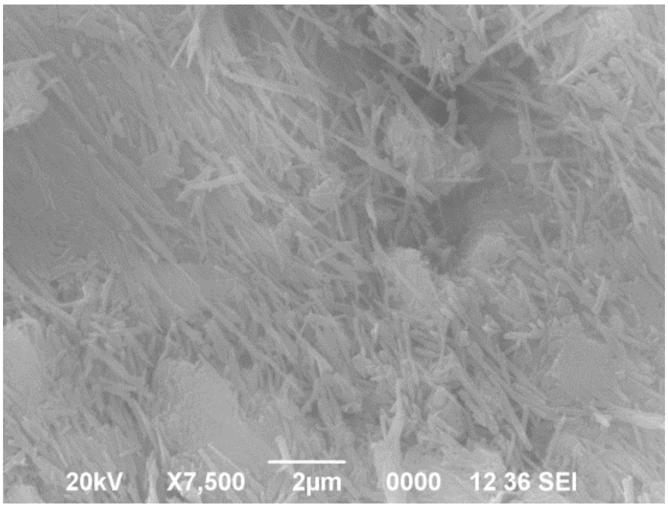
Table 3 Shear parameters determined from direct shear tests

| Shear parameters | | Degree of saturation, $S_r$% | | | | |
|---|---|---|---|---|---|---|
| | | **9%** | **20%** | **40%** | **70%** | **95%** |
| Cohesion, c in kPa | Undisturbed | 3.85 | 4.66 | 5.55 | 2.29 | 0 |
| | Remoulded | 1.53 | 2.48 | 2.74 | 1.57 | 0 |
| Angle of friction, φ in degree | Undisturbed | 39.7 | 37.7 | 33.8 | 30.5 | 19.8 |
| | Remoulded | 34.1 | 31.3 | 29.8 | 27.1 | 12.3 |

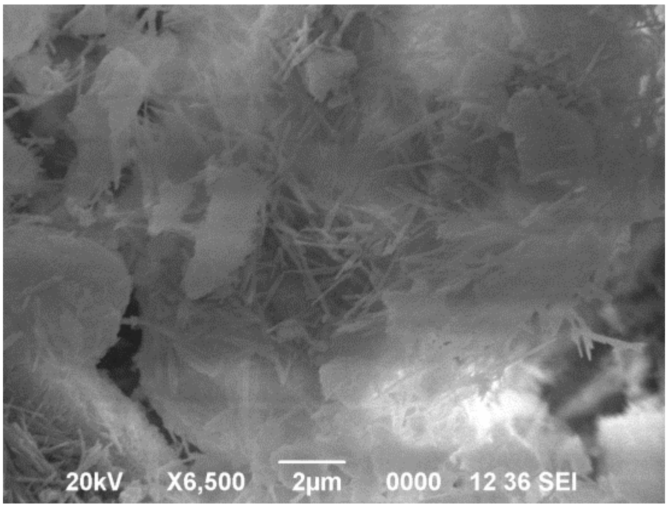
## 4. MICROSTRUCTURE OF THE SAPROLITIC RESIDUAL SOIL SAMPLES

The Scanning Electron Microscopic (SEM) test was carried out to observe the microstructure of both undisturbed and reconstituted samples of the saprolitic residual soil. Previous SEM based study (Huat et al., 2008) on changes in micro fabric of granitic and sedimentary residual soil (wetted from dry to full inundation condition) indicated that these tropical residual soils collapsed under inundation conditions due to loss of cementation and/or suction bonding between particles as a result of wetting. The collapse process leads to a reduction of voids and denser packing of the soil particles. The SEM results obtained in the present study for the saprolitic residual soil are shown in Figure 6(a) and Figure 6(b) for undisturbed and reconstituted samples, respectively. It is observed that in the undisturbed sample, the soil particles are enveloped with oriented curly threads of size between 1/10 μm and 1 μm (Figure 6(a)), whereas the threads are broken and dispersed in the case of the disturbed sample (Figure 6(b)). This size range indicates the presence of colloids in the soil, which are suspended particles in the size range between 1 nm and 10 μm, and they include abiotic colloids (clay, metal oxides, etc.) and biotic colloids (virus, bacteria, etc.) (Bin et al., 2011). Mahanty et. al in their study on the effect of duration of dry-wet cycle on mobilization of in situ colloids in intact heavily weathered saprolite soil cores, found that colloids are mobilized by infiltrating rainwater in saprolite, the amount of which depends on the duration of drying spell, and the permeability of the flow path in the saprolite soil. Electron microscope is the only instrument capable of measuring the size of particles in the colloidal range (1 nm to 1 μm) (Goldberg et al., 2011). No reported SEM images of saprolitic residual soil could be found in the literature.

In colloid transport through soil in unsaturated conditions, the colloid particles tend to adsorb almost irreversibly onto the water-air interface (Bin et al., 2011). As already mentioned, the saprolite soil in the hill is mostly unsaturated. So, it is reasonable that the clay colloid in this unsaturated saprolitic residual soil provides the additional bonding between the soil particles and results in the soil's brittle strength.




(a) Undisturbed sample




(b) Reconstituted sample

Figure 6 SEM images showing micro fabric of the saprolitic residual soil samples

## 5. STABILITY ANALYSIS OF THE SLOPES

Stability analysis of the hill slope constituted with the saprolitic residual soil was carried out using strength parameters obtained for both undisturbed and remoulded samples. Figure 7 shows the typical slope profile used in this analysis. The height of the slope was taken a 10 m. The inclination of the slope was assumed to be within the range $35^0$ and $85^0$. The groundwater table was taken to be at great depth. These dimensions were assumed based on the field condition of the hill slopes under study. Furthermore, the trial slip surfaces were assumed to be circular and lie above the toe of the slope. This assumption is also based on field observation of the previous slope failure cases in the study area, where nearly all failures were shallow depth failures located above the toe.

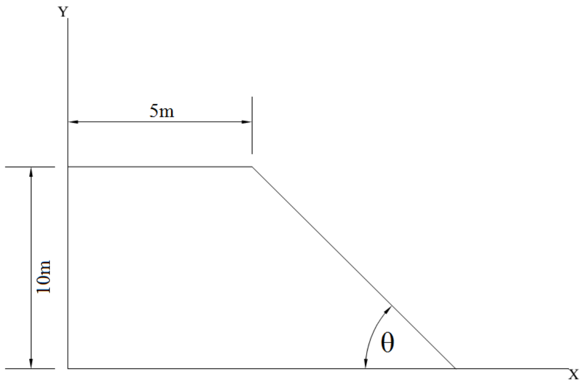



Figure 7 Typical slope model with slope inclination θ

Factors of safety were computed for slopes with inclination of $35^0$, $45^0$, $55^0$, $65^0$, $75^0$, and $85^0$ with the horizontal. Each of these slope profiles was analysed for 9%, 20%, 40%, 70%, and 95% degrees of saturation of the slope soil. This analysis, carried out in SLOPE/W software, was conducted to study the effect of sample disturbance in the stability assessment of saprolitic residual soil hill slopes. The Factors of safety thus obtained are compiled against the slope angle for both undisturbed and remoulded cases are presented in Figure 8.

(a)

(b)

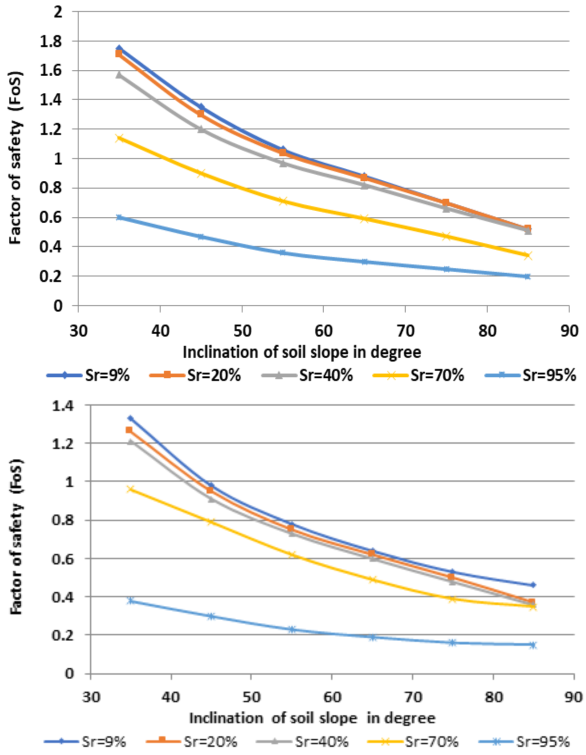



Figure 8 Decrease in FoS with Slope angle for different Sr%: (a) for undisturbed samples and (b) for remoulded samples

From Figure 8, the critical slope angles corresponding to FoS = 1 are determined and presented in Table 4.

Table 4 Critical slope angle computed from strength parameters of undisturbed and remoulded soil samples

| | Degree of saturation, $S_r$% | | | |
|---|---|---|---|---|
| | **9%** | **20%** | **40%** | **70%** |
| Remoulded soil sample | $44^0$ | $43^0$ | $42^0$ | $33^0$ |
| Undisturbed soil sample | $59^0$ | $57^0$ | $54^0$ | $41^0$ |
| Gain in critical slope angle for undisturbed case over remoulded case | $15^0$ | $14^0$ | $12^0$ | $8^0$ |
| % gain in critical slope angle for undisturbed case over remoulded case | 34 | 33 | 29 | 24 |

As the undisturbed strength parameters have shown higher stability of the slops, the percentage gain in stability in terms of critical slope angle in undisturbed soil conditions over remoulded soil conditions at different degrees of saturation are also determined and presented in Table 4.

## 6. DISCUSSION

The hill slopes in saprolitic residual soil under study often undergo localized rain-induced failures. The study area, situated in the northeastern part of India, receives average yearly rainfall of more than 1500 mm. The rainfall mostly occurs during the active monsoon period from June to September, while the period from November to March is generally dry with negligible precipitation. The groundwater table of these hills is very low; the degree of saturation of the hill cut slopes basically varies with evaporation and infiltration conditions during the alternate dry and wet seasons. The natural slope gradients of these hills were cut for the road construction activities resulting in steeper gradients. Although most of these steep cut slopes remain stable shallow depth failures above toe level of the slopes were observed in many locations during the rainy seasons. With increasing degree of saturation, the decrease of values of shear strength parameters of the slope's soil, as observed in Table 3, leads to decline in stability condition of the slopes. From the stability analysis results of the slopes, plotted in Figure 8(a), it is observed that a $45^0$ slope at degree of saturation below 40% having FoS greater than 1.2 is found to be in the verge of failure if the degree of saturation rises to nearly 70%.

From Table 4, it is observed that the stability analysis using soil parameters obtained from reconstituted samples of the saprolitic residual soil gives conservative results. The soil slope can stand on its own at slope angles that are steeper by 20% than those predicted using strength parameters of reconstituted soil samples. At 70% degree of saturation, a slope with a critical inclination of $33^0$ predicted based on reconstituted sample strength parameters can remain stable at an inclination of $41^0$ in undisturbed conditions. With the initiation of instability conditionss, such a slope may quickly lose the additional strength of undisturbed soil and result in sudden failures.

## 7. CONCLUSIONS

The existence and effect of cementing property of intact saprolitic residual soil in stability analysis of hill cut slopes of this residual soil was studied through a laboratory testing program. A modified procedure for the collection of undisturbed samples of the saprolitic residual soil for direct shear test was proposed and adopted. The following observations and conclusions are made from the study:

1) The existence of clay colloid in the undisturbed saprolitic residual soil possibly provides the additional bonding between the soil particles and results in the soil's brittle strength.
2) The angle of internal friction of the undisturbed samples is found to be on average, 15% higher than the angle of internal friction of reconstituted samples.
3) With the increase in the degree of saturation, the friction angle value decreased for both undisturbed and disturbed samples. For the undisturbed samples, the friction angles decreased by about 23% from $39.7^0$ at dry condition (9% degree of saturation) to $30.5^0$ at 70% degree of saturation. In contrast, it decreased by about 20% from $34.1^0$ at dry condition (9% degree of saturation) to $27.1^0$ at 70% degree of saturation for the reconstituted samples. The friction angles were found to be as low as $19.8^0$ and $12.3^0$ for nearly full saturation of the undisturbed and reconstituted samples, respectively.
4) The cohesion values are low though the undisturbed samples have shown higher values (average 4 kPa) compared to reconstituted samples (average 2 kPa).
5) The critical slope angles computed using undisturbed soil parameters are found to be at least 20% steeper than the critical slope angle based on reconstituted soil parameters up to 70% degree of saturation. At near full saturation (95% degree of saturation), the slopes are found unstable even at a slope angle of $35^0$.
6) The critical slope angle decreased from $59^0$ at $S_r$ = 9% to $41^0$ at $S_r$ = 70% for undisturbed soil parameters, whereas for reconstituted soil parameters, the critical slope angle decreased from $44^0$ at $S_r$ = 9% to $33^0$ at $S_r$ = 70%. The % gain in critical slope angle for undisturbed cases over disturbed cases decreased with an increase in the degree of saturation.

It can be concluded that the presence of weak cementing bond resulted in higher stability of hill slopes in the undisturbed saprolitic residual soil in comparison to slopes in the same soil under disturbed conditions. If, due to any reason, instability is initiated in the undisturbed saprolitic residual soil slopes, the loss of cementing the bond of the soil due to this disturbance may expedite the failure process and result in sudden failures.

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