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Causes of debris flow in clayey soils in the hill tracts of Bangladesh

M. Kamal Uddin

Institute of Appropriate Technology
Bangladesh University of Engineering and Technology Bangladesh, Dhaka 1000, Bangladesh

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Abstract

The causes of debris flows in clayey soils were studied by carrying out some tests. Several important conclusions are drawn about shear strength properties, creep properties and swelling pressure of clay and their influences on debris flows. Boundary surface layer of clay plays a key role in causing soil flow. Owing to water percolation during rainfall, cohesion, effective stress and frictional resistance of surface layer diminish. In this process, the upper slipping layer of clay stratum undergoes swelling against overburden pressure and thus shear strength reduces. Fluidization occurs due to reduction in internal shearing resistance because of momentum transfer between particles while the flow is in a dispersed state settings. It is concluded that the main causes of debris flow in clayey soils are pertaining to reduction of shear strength of clay surface layer, swelling pressure and creep deformation. Finally some preventive measures have been discussed to counter critical debris flow situations.

Keywords: Debris flow, clay, soil, hill tracts, Bangladesh

1. Introduction

A large portion of the south-eastern part of Bangladesh forms the hill tract where the soil flow occurs during intense rainfall in the rainy season. The physiographic features of this area comprise Tertiary and Pleistocene hill formations. Based on surfacial geology, the pattern of landform relevant to debris flow in Bangladesh is termed as Alluvial Terrace and Hilly deposits. The Raised Alluvial Terrace deposits or Pleistocene deposits comprise of clay indicating presence of Illites, Kaolinite, quartz, etc. The general characteristics of Hill soils correspond to variable soil types, which are function of underlying geology. Generally, silty or sandy clays and clays grade into disintegrated rock at shallow depths are encountered. Most of the soil flows in this area arise in the clayey type of geological and geomorphological settings. Figure 1 shows the scar of debris flow in Bandarban Hill tract. Recently, in Bandarban, Khagrachari, Rangamati, Baghaichari and other hill tracts, severe debris flows occurred in clayey deposit, causing huge casualties (according to a reconnaissance survey done by the author, 2003). Some general types of debris flows that occur in the clayey deposits in these areas are:

(1) Resulted from erosion and shallow scale instability owing to intense rainfall in the flocculated structured soil zone.
(2) Due to fluidization of poorly compacted fill during infiltration of rainwater.
(3) Large-scale instability and liquefaction in soft cohesive soil and flow of soil debris through steep and narrow gorge in between the hills.
(4) Avalanches of mud during rainfall, where a large volume of the soil slurry acquires remarkable mobility.

From the investigation of the reconnaissance survey done by the author (2003), it was found that about 75% of the soil debris flow occur in the clayey geological settings in the hill tract of Bangladesh. To understand about the debris flow, it is very important to study the mechanical property of clay existing in the flowing surface.

Fig 1. Scar of Debris Flow in the Clayey Soil of Bandarban District in the Southeastern Part of Bangladesh

The characteristics of debris flows are highly depended on the geology or mechanical properties of soil of the relevant regions [Hsu (1975), Langford et al. (1990), Oyagi et al., (1983)]. This paper is a part of a comprehensive research program recently conducted wherein attention is focused on the causes of debris flow in clayey region. The study of debris flow was been carried out by some tests using sophisticated direct shear testing machine. Attempt was made to find relation between mechanical properties of clay and debris flow initiation. Some potential controlling measures have been briefed in the paper as well.

2. Debris flow and rainfall

The study was based on the hilly soils of south-eastern part of Bangladesh. Table 1 shows some typical soil properties in these areas. It is well known that debris flow occurs severely in heavy rainfall. Due to rainfall and/or rising of ground water table, reduction of effective stress occurs which in turn reduces frictional resistance of soil. Debris flow occurs due to loss of effective stress and frictional resistance of soil particles. The velocity increases just before the occurrence of a debris flow. The frictional resistance conditions change from the static to the kinetic state.

When a soil structure possesses a dispersed state having inadequate compaction, soil strength attains a low value. The rainwater falling on the surface of loose soil can percolate readily into soil mass, wetting the soil up to an appreciable depth and reduces the strength further. For saturated soil, during rainfall, soil may collapse, lose its strength, liquefy and cause mud avalanches. Some failure causes from the development of seepage conditions within the wetted zone as water percolates the face of the slope. The strength-losing phenomenon of the layer causes downhill movement. Thus the surface layer of the clay converts instantaneously into mud avalanches possessing a high momentum.

Table 1
Typical Soil Properties

Soils	Bandarban Soil	Khagrachari Soil	Rangamati Soil	Chittagong Soil	Baghaichari Soil	Barkal Clay
Liquid Limit, WL(%)	42	56	41	40	51	67
Specific Gravity, Gs	2.681	2.687	2.684	2.686	2.652	2.668
Plasticity Index, Ip	21	29	22	21	19	44
In-situ Dry Density (kN/m3)	11.94	13.41	12.65	12.10	15.89	14.40
Optimum Water Content (%)	31	35	34	44	17	28
Grain Size Distribution						
Clay:	20	27	28	25	14	75
Silt:	75	66	67	70	24	20
Sand:	4	5	3	4	47	4
Gravel:	1	2	2	1	15	1
Soil Classification as per Unified System	CL	CH	CL	CL	SM	CH

3. Rainfall and surface layer of clay

In case of saturated clay, void ratio and water content are almost constant and shear strength does not vary significantly. Thus in debris flow, it is very important to study the relationship between rainfall and clay surface strength rather than to investigate the shear strength of the clay itself. Direct shear machine was used to study the surface boundary layer of the clay deposit.

The mobility of soil particles is primarily contingent on the strength parameters of the moving mass. In conventional analysis within the framework of limiting equilibrium, the shear strength parameters required to equilibrate potential sliding mass are compared with the available strength parameters. If the factor of safety is less than unity, there is an imbalance between driving forces and resisting forces, and the soil mass will accelerate. The subsequent motion may be translational or rotational and can be readily calculated within the framework of rigid body mechanics provided the resistance along the base of the moving mass is known throughout the motion.

The surface of clay plays the most important role in the process of debris flow initiation. This boundary layer initiates the soil mobility as a consequence of alteration of its soil parameters. The cohesion of the surface boundary layer begins to diminish, when the percolated water of rainfall reaches the contact surface of the clay. Tests were carried out on Baghaichari soil in order to find out the variation of shear strength of surface layer with addition of water. Figure 2 shows relationships between shear strength and cumulative hours of water supply for soil specimens of Baghaichari hilly area. Three kinds of soil specimens with low, medium and high water content were tested.

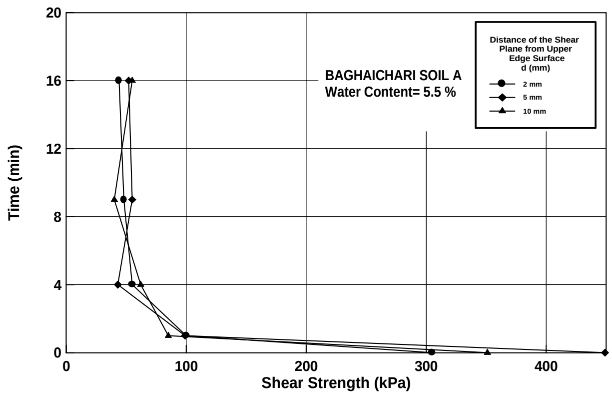

Fig 2a. Variation of Shear Strength with Water Supply Duration Baghaichari Soil A)

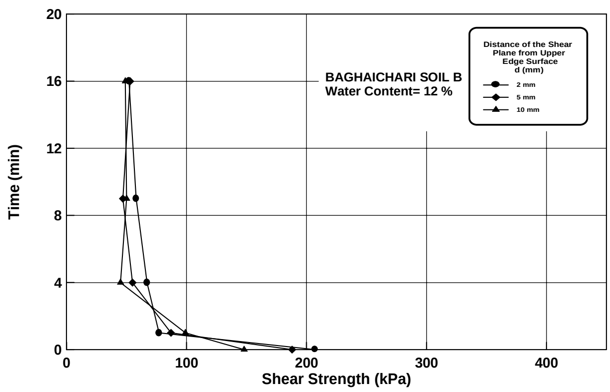

Fig 2b. Variation of Shear Strength with Water Supply Duration (Baghaichari Soil B)

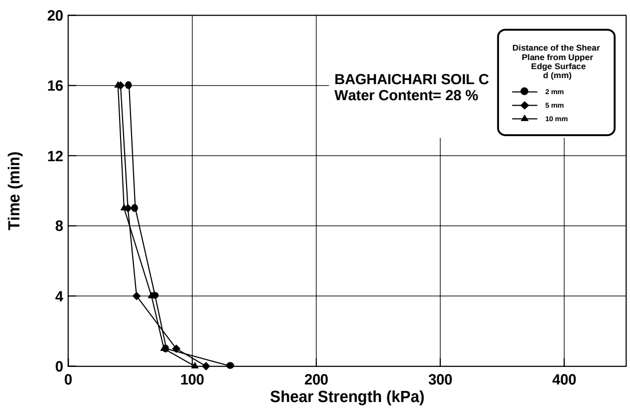

Fig 2c. Variation of Shear Strength with Water Supply Duration (Baghaichari Soil C)

Figure 2(a) shows that for the soil specimen with low water content (w=5.5%), on every shear plane the shear strength decreased rapidly as soon as the water was supplied (in about 1 minute), then the strength remained almost constant. This is because, coefficient of the permeability of soil specimen was much higher and thus the specimen was saturated in very short time. This way the shear strength reduced within a short time. After getting saturated, the shear strength did not vary and remained almost constant. This interpretation is supported with some types of tests in the second and third tests with medium and high water content (w=12% and 28%) as shown in Fig 2.(b) & (c).

In the second test, with medium water content (12%), a moderate change of shear strength was noticed, while in the third test with higher water content (28%) when water was supplied, the change of shear strength was very small. Figure 3 shows tests with Barkal clay showing the strength characteristics of the clay as a function of time of water supply. Barkal clay has low value of coefficient of permeability.

From Fig. 3, it is revealed that shear strength of Barkal clay changed very little with duration of water supply. Figure 4 shows the variation of shear strength of boundary layer of Barkal clay with various types of water content such as air dried, saturated surface dry and wet condition. 'Air dried' means the condition when water of specimen's surface is soaked with a filter paper and the surface is dried by micro-electric stove. 'Saturated surface dry' corresponds to the condition when surface water of the specimen is only removed (with filter paper). On the other hand, 'wet' refers to the condition when surface of the specimen is sufficiently full of water. It is obvious from the results that higher the water content in the specimen, smaller shear strength. Thus in the case of hilly soils which have higher co-efficient of permeability, it can be postulated that shear strength decreases directly due to rainfall. For a clay having low value of permeability (such as Barkal clay, Fig. 3), rainfall does not affect the strength of the clay very much. However, due to effect of water content of boundary layer, shear strength decreases (Fig. 4).

4. Swelling pressure of clay

Shear strength of the clay decreases due to increase of moisture content in the boundary layer of the clay. In turn, wetness of the clay is related to its swelling characteristics. Swelling process will be initiated, when overburden pressure is smaller than the swelling

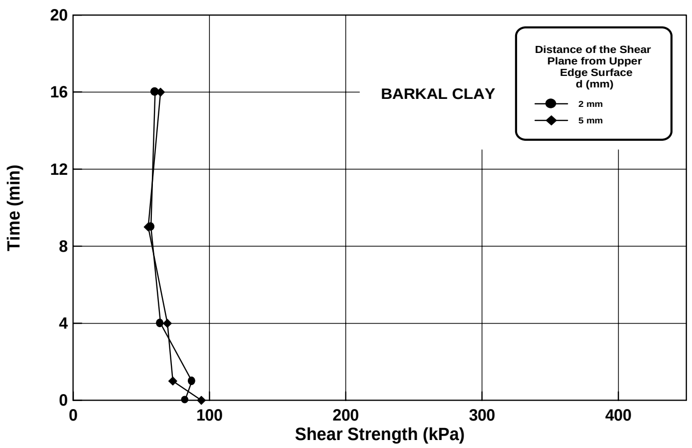

Fig 3. Relationship between Shear Strength with Water Supply Duration (Barkal Clay)

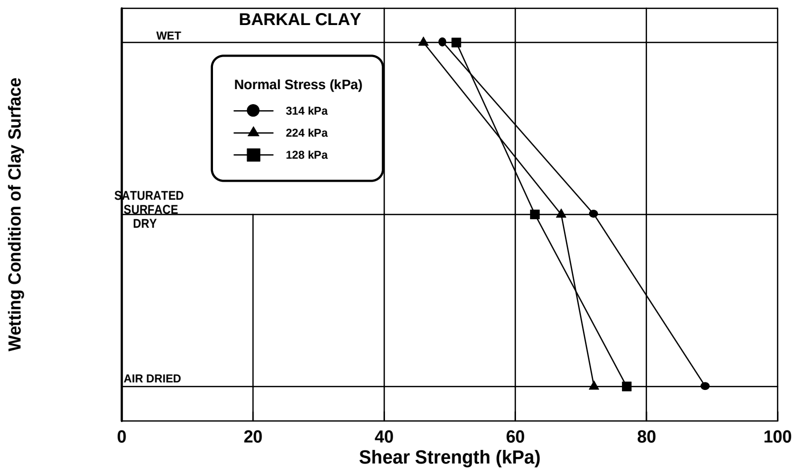

Fig 4. Variation of Shear Strength at Various Wetting Conditions of Clay Surface (Barkal Clay)

pressure. Swelling reduces the shear strength of the boundary clay layer and debris flow occurs. It is very important to study the effect of swelling pressure and its characteristics.

5. Relationship between time and swelling pressure

The time required to reach a constant value of swelling pressure is shown in Table 2. Barkal clay is not shown in the table as it takes many hours to reach a constant swelling pressure. It is found from the test results that for a clay, with lower initial water content or larger dry density, it takes a longer time to reach a asymptotic or constant value of swelling pressure. A soil possesses high value of swelling pressure which contain of clay mineral such as montmorillonite, and it takes a longer time for the soil to reach a constant swelling pressure (e.g., Barkal clay). Table 3 shows swelling pressures of some of the soils of Table 1. It was seen that swelling pressure became larger than overburden pressure in many cases. Thus it is quite rational that swelling would occur and the shear strength of the clay would reduce. Figure 5 shows variation of swelling pressure with initial water content, and dry density ratio of Khagrachari soil.

Thus it is important to be careful when countermeasures to be adopted to control debris flows in those soils which contain clay mineral such as montmorillonite. For the above reason, in the case of non-montmorillonite soils, controlling measures against debris flow is not problematic as these soils attain constant swelling pressure within a short time. However, whatever may be the soil category, necessary countermeasures against debris flows are to be adopted immediately as soon as it is expected or begins. The following predicting equation of swelling pressure of Hirata. and Chishaki (1983) was used in the study:

PS=4910.4(ρd/ρd(max))5.5log(wL/wo)

where, PS = Swelling pressure, ρd = Dry density, wL = Liquid Limit, wo = Initial Water Content

Table 2
Time Required to Reach a Constant Swelling Pressure

Soils	Initial Water Content	Time (min) ρd/ρd(max)=1.0	ρd/ρd(max)=0.9	ρd/ρd(max)=0.8
Bandarban Soil	12	36	9	7
	20	65	8	7
	31	32	18	2
	42	16	8	3
Khagrachari Soil	7	13	3	3
	15	11	3	3
	28	4	3	3
	40	12	3	3
Rangamati Soil	12	33	30	8
	23	32	29	3
	34	12	19	2
	43	8	4	2
Chittagong Soil	6	10	5	2
	18	10	5	2
	28	6	4	2
	39	5	4	1.5

Table 3
Swelling Pressures

Soils	Initial Water Content w(%)	Swelling Pressures (kPa) ρd/ρd(max)=1.0	ρd/ρd(max)=0.8	ρd/ρd(max)=0.8
Bandarban Soil	8	131	101	51
	18	76	63	35
	31	49	37	19
	39	22	17	7
Khagrachari Soil	7	191	76	44
	15	99	34	29
	28	49	21	15
	40	32	15	12
Rangamati Soil	12	105	78	39
	23	99	74	12
	34	71	28	8
	43	13	12	7
Chittagong Soil	6	81	49	23
	18	39	18	11
	28	8	6	4
	39	12	8	6
Barkal Clay	9	296	130	74
	20	159	91	42
	32	91	52	26
	39	32	23	15

6. Soil strength reduction due to swelling

The reduction of shear strength due to swelling was investigated by carrying out direct shear tests on Barkal clay. Table 4 shows results pertaining to reduction of shear strength due to swelling of Barkal clay. The SR value refers to shear strength ratio pertaining to swelling of a clay and is defined as:

$$\mathrm{SR} = \frac{\text{Shear Strength after Swelling}}{\text{Shear Strength at Non-Swelling Condition}}$$

The SR values of the clay reduced to 0.51 corresponding to swelling value of 1 mm which is 5%. Swelling of clay can not be ignored in the mechanism of the debris flow. As soon as the water permeates into the clay boundary surface with low water content, swelling occurs against overburden pressures and thus shear strength of the clay may largely reduce.

7. Creep strength of clay

The debris flow is a typical shear creep phenomenon. When rain water percolates into the ground, the density and the shear stress of the clay on the flow slipping plane increase. When the shear stress on the slipping plane becomes greater than the shear strength, the clay becomes greater than the shear strength of the clay resulting a debris flow.

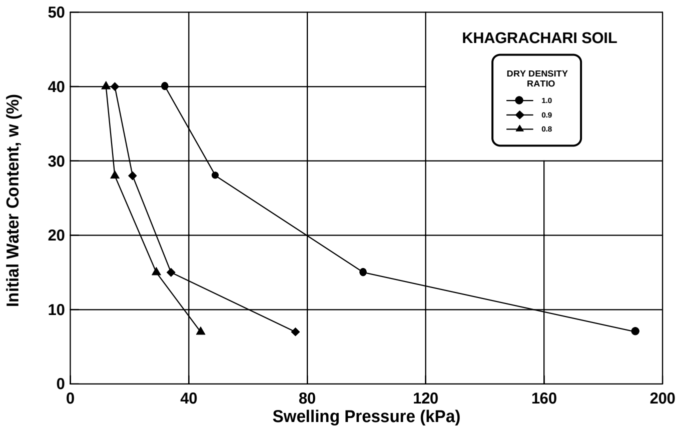

Fig 5. Relationship between Swelling Pressure, Initial Water Content and Dry Density Ratio (Khagrachari Soil)

Table 4
Reduction of Shear Strength of Due to Swelling of Barkal Clay

Swelling Value (mm)	Maximum Shear Stress (kPa)	Value of SR
0	111	1.00
0.25	108	0.97
0.50	67	0.60
0.75	61	0.55
1.00	57	0.51

In order to investigate the relevant creep phenomenon, creep tests for some soils of Table 1 were carried out by direct shear test machine. In the analysis, the ratio of upper yielding shear stress and direct shear strength was denoted by S, as follows.

$$S = \frac{\text{Upper Yielding Shear Stress } (\tau_y)}{\text{Direct Shear Strength } (\tau_{DSS})}$$

With the test results, a regression equation was obtained as follows:

$$S = -0.00592\, I_p + 0.97 \qquad (1)$$

The equation (1) is useful in practical application. It can be noted that the equation is independent of dry density (ρd) and water content. For some soils such as Barkal clay, the value of S is affected not only by plasticity index but also by dry density and water content. Thus the equation gives an approximate estimation of the value of S and requires to include the effect of dry density and water content. The parameters τDSS and Ip can be determined from simple conventional laboratory tests. The approximate upper yielding value (τy) for clays susceptible to flow can be easily estimated by a simple laboratory tests.

In order to further support the validity of above equation, direct shear creep test was carried out in addition. In the test series three factors (i.e. plasticity index, dry density ratio and water content) were considered each with two values (Table 5). The effects of dry density, water content and plasticity index on creep shear strength were investigated using the method of variance analysis (VA).

Table 5
Factors Considered in Direct Shear Creep Tests

Factors	Symbol	Level 1 (Symbol/Value)	Level 2 (Symbol/Value)
Dry Density ratio (ρd/ρd(max))	A	A1 1.0	A2 0.8
Plasticity Index (Ip)	B	B1 21.0	B2 45.0
Water Content (w)	C	C1 Wopt + 5	C2 Wopt - 5

Table 6
Test Cases and Factors Combinations in Direct Shear Creep Test

Case	Test Case 1	Test Case 2	Test Case 3	Test Case 4	Test Case 5	Test Case 6	Test Case 7	Test Case 8
Dry density ratio ρd/ρd(max))	A1	A1	A2	A2	A1	A1	A2	A2
Plasticity index (Ip)	B1	B2	B1	B2	B1	B2	B1	B2
Water content (w)	C1	C2	C2	C1	C2	C1	C1	C2

Table 6 shows the parameters used in eight test cases of direct shear creep tests. The result shows that dry density, water content and plasticity index effected on creep strength in order respectively, former being greater influencing parameter than the later. Some test results showing the Coulomb's failure lines are presented in Fig. 6. The direct shear creep test result is shown by dotted line (σ-τy), while firm line appends (σ-τDSS) line. Debris flow in clay region shows typical creep deformation phenomenon. The method for debris flow analysis presented above is based on laboratory data and thus the analytical process can be applied in all practical cases.

8. Some controlling measures of debris flow

It is possible to provide protection against debris flows in various ways. Conventional method to protect from debris flow is by constructing protective structures. Some measures have been cited by Oyagi et al., (1983). Systematic clearing of the source can be carried out and retention dam can be constructed. Sometimes dike is constructed to protect town from uphill debris flow. Protection works against a proposed design flow can be modelled on a rational basis. Design should proceed more with considerations of fluid mechanics rather than with traditional concepts of solid mechanics. Previous natural occurrences can be used as a calibration in order to find out the appropriate modelling medium.

In many cases, mobility arises from the collapsing nature of the soil. Thus compaction of soil can greatly reduce soil flow. Plantation holds enormous potential in acting as a countermeasure against debris flows in a slope. Roots of plant assist in holding a flowing surfacial soil mass to its base, and it is therefore necessary to consider their influence on the shearing resistance of the soil. Roots of tree stretch to a deeper level and help holding a slipping soil by serving to augment the shear strength of soil.

Huge debris avalanches are catastrophic events. Stabilizing such large masses can be considered to prevent instability where large debris avalanches are expected. It is essential to be able to estimate their motion if some form of protection is planned such as by zoning restrictions or by construction of protective structures. The retaining wall with large concrete blocks, prefabricated retaining wall can be used to prevent debris flow. The speed of a flowing soil mass is an important factor for measuring the impact force of a sliding soil mass. Construction of tied-back retaining wall can be most effective protection for a pier to be protected against destructive forces of surges. The forces to be resisted by the anchors can be calculated by evaluating the change in momentum of the debris flow. Traditional considerations of earth pressure are not appropriate for this design; an approach based on fluid mechanics is preferable. A flow can be arranged to slow down and stop by providing various types of obstacles such as concrete blocks, etc., in the flowing path. During the motion, if some obstacle is encountered, considerable resistance, up to the passive resistance of either the obstacle or the sliding mass would be developed. These forces are calculable from traditional concepts of earth pressure. For rotational or translational trajectories, the moving mass soon enters a regime where resisting forces are greater than the sliding forces. Thus the moving mass can be decelerated to stop.

In most cases, intensive rainfall causes erosion and mobility surfacial deposits. Huge mass of soil can be fluidized by virtue of energy transfer mechanism following instability. The moisture contents and pore water pressures of the soil in a mud flowing slope change largely according to the permeability of soils in the flowing slope. If rainfall can be reasonably forecast, the occurrence of debris flow can for more accurately predicted. Since debris flow occurs frequently in rain, it is important to probe the effect of rainfall on shear force, displacement and top layer strength of clay. A considerable effort is required to systematically classify soil flows and to understand the phenomenon and processes by which they become fluidized.

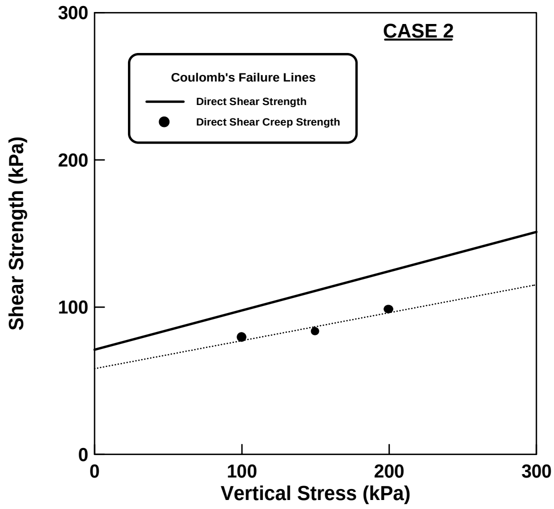

Fig 6a. Creep Shear Strength Test Showing Coulomb's Failure Line (Case 2)

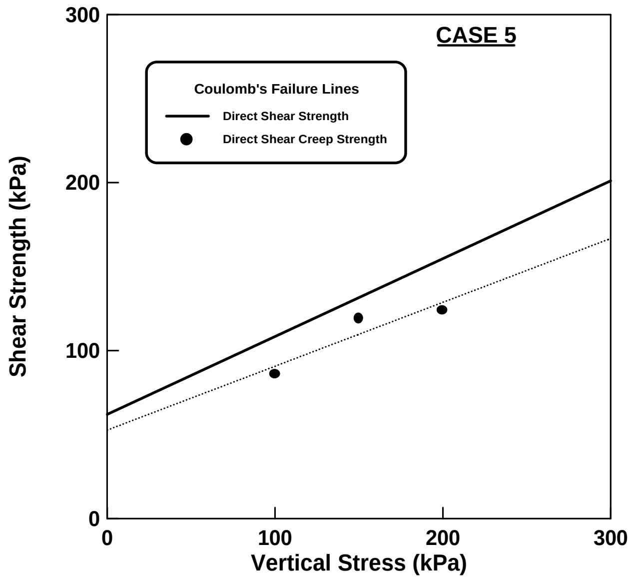

Fig 6b. Creep Shear Strength Test Showing Coulomb's Failure Lines (Case 5)

9. Conclusions

Tests on some soils in the hilly areas in the south-eastern part of Bangladesh have been carried out to study the effects of swelling and creep of clays in debris flows. From the tests results, the mechanism of debris flow in clay was understood. Some useful findings about strength properties, swelling pressure and creep properties of clays in debris flow were obtained. The presented method of debris flow analysis can be used in practical application in all cases. Some preventive measures against debris flow also have been discussed in the paper. Principles of fluid mechanics should be used to design protective structures in addition to common consideration of theories of soil mechanics.

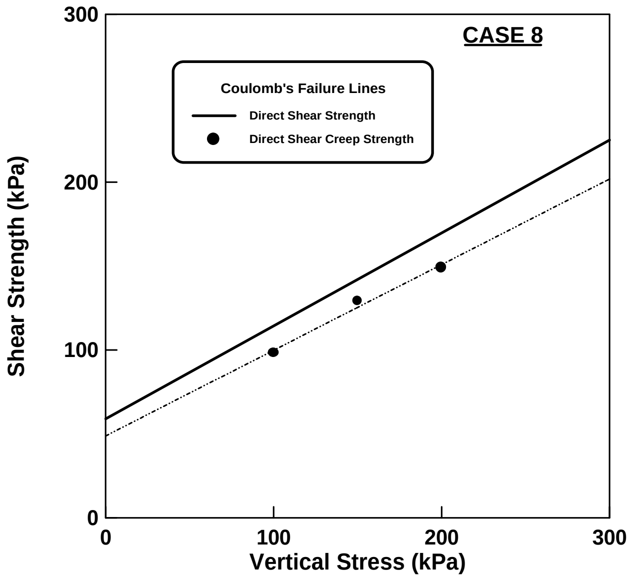

Fig 6c. Creep Shear Strength Test Showing Coulomb's Failure Lines (Case 8)

It is revealed that boundary layer is most dangerous layer to cause debris flow. Using sophisticated direct shear testing machine, it was found that the shear strength of Barkal clay did not change significantly. However, the shear strength of surface layer of Barkal clay reduced due to wetting. Thus it can be postulated that a significant change of shear strength of saturated clay does not occur due to rainfall. But shear strength of surface layer of a clay decreases due to surface wetting. Barkal clay showed large swelling pressure of 296 kPa, which indicates presence of clay mineral such as montmorillonite. When swelling value was 1 mm (5%), the value of SR (strength ratio pertaining of swelling to non-swelling condition) reduced to 0.51. Thus it is seen that when water reaches the clay boundary layer, it can undergo swelling against overburden pressure. When swelling pressure is larger than the overburden pressure, swelling would occur. Swelling greatly reduces the shear strength along the flow-slipping surface and debris flow would occur. So investigation of swelling characteristics of the clay is a basic part in debris flow analysis.

It was seen that the dry density, water content and plasticity index have effect on creep shear strength. For Barkal clay with large plasticity index, the parameter, ($S=\tau y./\tau DSS$), is greatly affected by dry density. Creep deformation occurs easily in soil of large plasticity index. Shear strength of boundary surface layer of Barkal clay greatly decreases due to wetting and swelling and creep deformation also occurs easily in this clay. Thus the clays are susceptible to flow in these areas. For such salient reasons, debris flow occurs frequently during the rainy season in this part of Bangladesh.

Symbols/notations

Gs	Specific Gravity
Ip	Plasticity Index

Ps	Swelling pressure
βd	Dry density
ρd (max)	Maximum Dry Density
S	The ratio of upper yielding shear stress and direct shear Strength
SR	A value that refers to the shear strength ratio pertaining to swelling of a clay
τy	Upper yielding shear stress
τDss	Direct Share Strength
w	Moisture content
wo	Initial water content
wL	Liquid Limit
Wopt	Optimum Water Content

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