SOME ENGINEERING PROPERTIES OF UDZUNGWA SCARP SOIL

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SYNOPSIS

The Udzungwa scarp is prone to landslide, slope instability, and severe erosion brought about by several interrelated factors like rainfall, soil geological formation, geomorphological feature of the slope and gross engineering properties of the soil available within the scarp. In this paper, some engineering properties of soil available within the scarp are discussed. Various soil engineering characteristics, erosion, and slope stability problems are pinpointed and discussed. This paper is based on the study carried out during pre-construction, construction, and post-construction investigation of 16 Km of Kihansi Dam Access road, which is traversing the Udzungwa escarpment.

1.0 INTRODUCTION

The Udzungwa scarp is located in Iringa region, extending its boundary to Morogoro region in Tanzania. This scarp is thought to be formed by scale block-faulting, up-heave, and tilting of the highlands relative to the lower land of Ruaha-Kilombero valley. There is no distinctive single fault zone, but several faults and fracture zones following different directions. The escarpment thus consists of a rugged, forest-covered mountainous landscape intersected by deep, narrow gorges and valley. The bedrock is frequently exposed in rapids, waterfalls, and steep hillsides [1]. The area around the scarp is experiencing heavy rainfall with annual rainfall ranging from 1000-1800 mm. The soil available in the scarp can be divided into two basic types:

1. Non-transported soil which is available on the highlands (elevation of 1100 m above sea level) formed by weathering of the parent granitic/biotitic gneissic rock. Depending on the nature of the parent rock and degree of weathering, the soil varies from clay, clayey silts, and sands. The colour of soil varies from red, brownish, pinkish, grey and yellowish.
2. Transported soil, which is available in Kilombero plain (elevation 280-300 m above sea level), which is assumed to be transported by rivers and streams and depositing in stream beds, rivers, and meanders on the plain.

This scarp is dominated by gneissic formation mainly in the form of biotitic or granitic gneiss. The geotechnical problems associated with this soil are different and in general, can be summarized by one or more of the followings:

1. The severe erosion in the area
2. The slope instability and landslides in the area
3. The presence of mica in the soil

In this paper, the geotechnical problems associated with soil available within the Udzungwa scarp are presented and discussed.

2.0 AREA OF STUDY

The study was confined to the area hosting Lower Kihansi Hydropower project and 16 Kms of the Dam access road, which traverse through the mountainous terrain of Udzungwa escarpment in the Usagara Orogenic belt within the rift valley system. The dam access road is constructed on mountainous terrain with an inclinometer of greater than 30 degrees and is crossing through areas of complex landslide and gully erosion. Numerous old and fresh erosion/landslide scars are visible along and outside of the Lower Kihansi Dam access road alignment.

3.0 SOIL PROPERTIES

The hilly terrains of the study area are covered with residual soil formed from weathering and disintegration of the gneissic bedrock. These soils are variable in colour from red, brownish, pinkish and yellowish. The thickness of the topsoil is very variable but is ranging from 0.1-0.5 meters. The topsoil is dark grey or dark colour with low to high organic content depending on the vegetation.

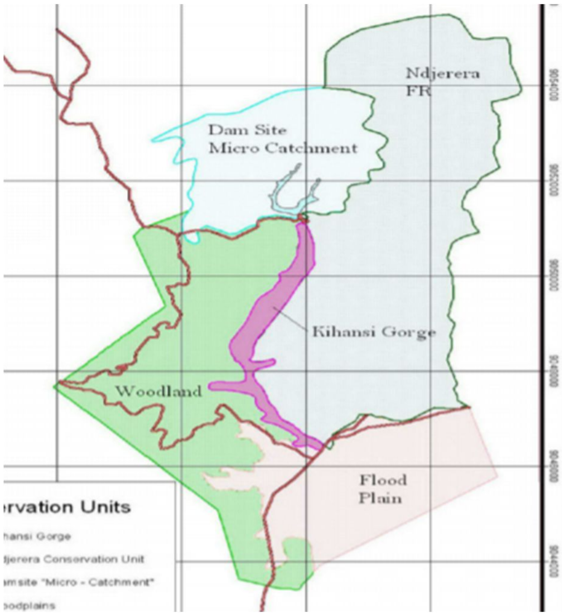

Figure 1: Land use map of Kihansi (source: Mwansasu, S. 2007. Ecological Monitoring Report)

3.1 Grading properties

The grain size of the soil is varying from clay, silt, silty sand, and clayey sand. The percentage of clay is variable depending on the degree of weathering and locations. However, the layer of soil having high clay content (clay content greater than 20%) is confined to the uppermost layers immediately after topsoil removal (zone of active weathering).

The depth of clay is ranging from 0.5-4 metres depending on the degree of weathering and locations. Below 4.0 metres, the most prominent soil is either silty sand or sand silty with low clay content. The grading envelope of forty-seven soil samples taken from various locations along the dam access road and dam site are given in Figure 2, while the proportional of clay, silt, and sand are presented in Figure 3, from which it can be seen that the soil available along the dam access road is clay, clayey silt, and a mixture of sand, clay, and silt with exceptional of areas which exhibited slope failure whereby it was found that the soil available along these sections are mainly silty sand with a very low percentage of clay.

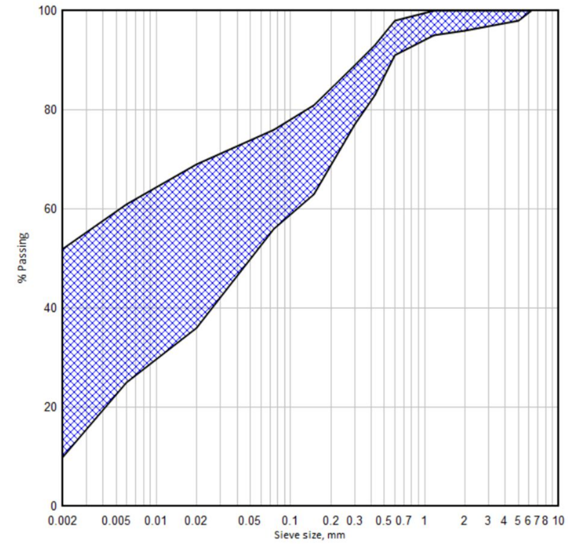

Figure 2: Grading envelope of 47 soil samples.

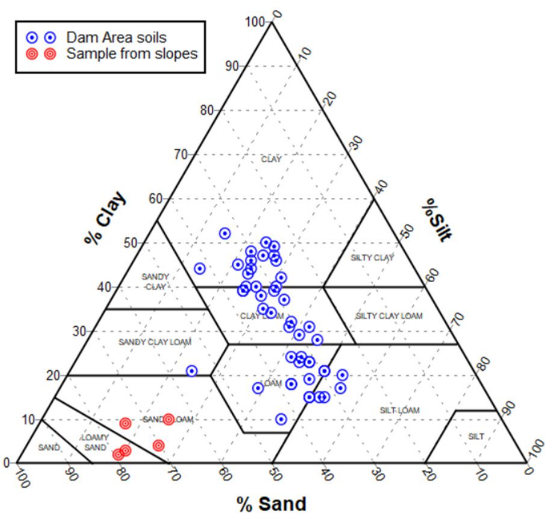

Figure 3: proportional of clay, silt, and sand

3.2 Plasticity data

Atterberg limit tests from the scarp soils yielded liquid limit ranging from 35 to 70 with a mean value of 53. The plastic limit varied from 24-43 with a mean value of 33. The soil samples taken in locations that exhibited slope failure was found to have a low liquid limit ranging from 33-35 and a plasticity index of less than 10. The plasticity of the soil in the project area is ranging from low plasticity to soil of high plasticity. About half of the whole soil samples are plotting below the A-line, suggesting that the main soil constituent of fine soils is likely to be silt or organic clay.

The position of soil on Casagrande A-Line chart is given in Figure 4. From the plasticity chart, it can be seen that the main clay mineral within the soil matrix is likely to be kaolinite since the majority of the soil plots within the band of kaolinite clay with few soil samples plotting within the band of illite clay.

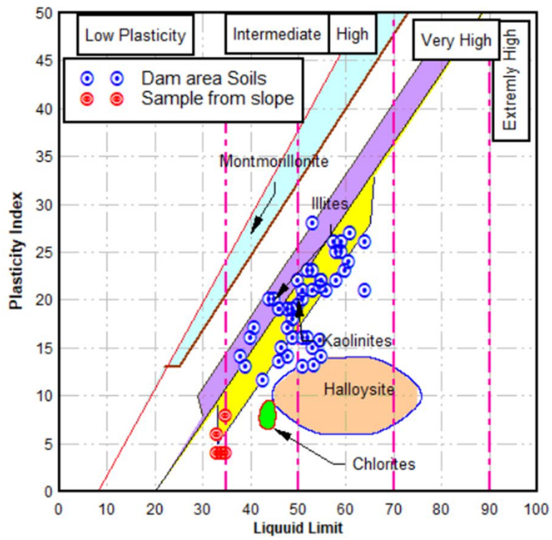

Figure 4: the position of Udzungwa soil on Casagrande A-Line plasticity chart

3.3 Activity and Expansivity Potential

Skempton (1953) [13] defined activity as the ratio of plasticity index to clay fraction and showed that clay activity could be related to the mineralogy and geotechnical history of the sediment. He classified clays into three groups, namely; "inactive" (Activity of less than 0.75), "normal" (activity of more than 0.75 but less than 1.25" and "active" clays (activity of more than 1.25). Skempton (1953) showed that for clay deposits, an approximately linear relationship existed between the plasticity index and the percentage of clay within the soil matrix.

Since the plasticity index is the range in water content over which a soil exhibits "plastic" behaviour, it would be expected that for two soils with the same clay content, the more active mineral soil, e.g., montmorillonite, would show a higher plasticity index. The tested Udzungwa scarp soil sampled within the dam site area is having clay activity ranging from 0.359 to 1.647 with an average of 0.693, suggesting that the clay available within the scarp can be classified as inactive clay since the majority of the soil samples plots within the band of inactive clay with handful soil samples plotting within the band of normal clay. Four out of forty-seven tested soil samples plotted marginally within the band of active clay. For the soil sampled from locations that exhibited slope failure, the activity of soil was found to be in the range of 0.6-2.0. The position of soil on Skempton Activity chart is given in Figure 5, from which it can be deduced that the principal clay mineral in order of relative abundance is likely to be Kaolinite and Illite echoing the classification of the clay minerals done based on the position of soil on the plasticity chart which also suggested the same clay minerals.

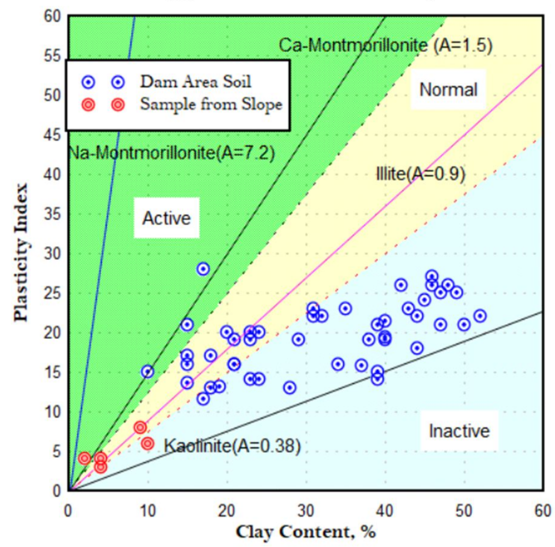

Figure 5: Position of soil on Skempton activity chart

Figure 6 and 7 shows the volume change potential of the Udzungwa scarp soil using Seed et al [14] and Van Der Merwe chart [6]. The data indicates that the Udzungwa scarp soil has low expansive potential as the majority of the soil samples falls in the low to medium expansivity class as assessed using both methods of Seed *et al.* and Van de Merwe. In Seed at al chart, the soil is having swelling potential (S) of between 1.5% (low) and 5% (medium). The majority of the soil sample falls within the band of low expansivity potential, i.e. swelling potential of less than 1.5%.

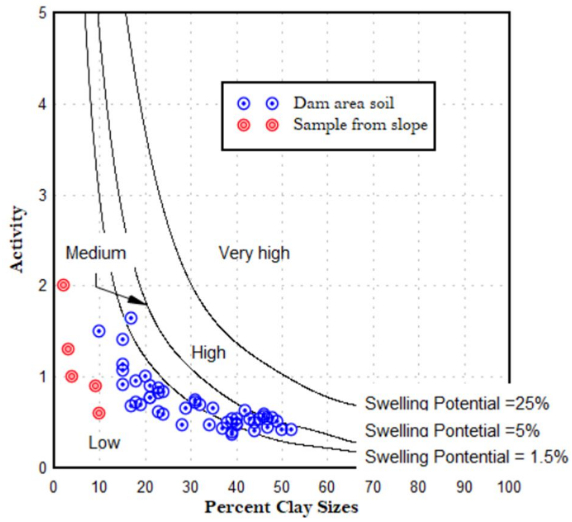

Figure 6: classification chart for swelling potential [14]

Based on Figures 6 and 7, it can be seen that the soil can be classified as low to a medium swelling potential, which also suggests that soil available within the Uduzungwa scarp is not containing an expansive clay mineral i.e. montmorillonite. The plot of soil on the plasticity chart suggests the same, i.e. the possible clay minerals within the soil is kaolinite and illite. For the sol sampled from the areas which exhibited slope failure, all five soil samples showed to have low expansivity potential.

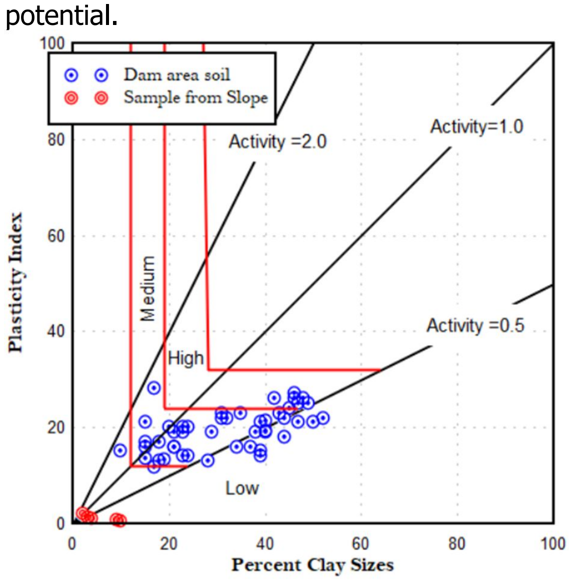

Figure 7: classification chart for swelling potential [23]

4.0 SOIL EROSION AND SLOPE STABILITY

The main types of soil movements which are affecting the slope along the Udzugwa scarp can be described by one or more of the following: -

1) Slope wash caused by rainfall
2) Piping
3) Landslides

4.1 Slope Wash, Piping and landslide

The area around the Udzungwas scarp is experiencing heavy rainfall with annual rainfall ranging from 1000-1800 mm. The area around this scarp is also experiencing severe landslide and erosion, in particular during the rainy season. It has been established that due to the geological formation and the geomorphological feature of the area, the rain is one of the factors responsible for initiating erosion and landslide mainly due to overland flow.

It has been observed that the high rate of surface runoff, which develops after the occurrence of rainfall, results in a high concentration of water, which flows into numerous cracks, fissure, and gullies existing along Udzungwa scarp area. The high inflow of water vertically through open cracks and laterally through the highly erodible, collapsible and permeable beds existing below the topsoil attains seepage velocity (force) high enough to remove the soil particle in suspension. Through this, piping erosion is initiated, and slope stability is affected. It was established that the area along the Udzungwa scarp is full of open interconnected networks of soil pipes. It is postulated that during Lower Kihansi Dam access road construction, especially during the cut and fill operations, some of these open soil pipes were blocked. In the rain season, these pipes are filled with water through seepage from the soil matrix or by direct entry into the pipes from the ground surface. The hydrostatic head from the water standing in the soil-pipe produces high pore pressures in the soil around the pipe. This increase in pore pressure is usually associated with soil shear strength reduction, which results in the collapse of the slope in cutting. During the construction of Dam access road, slope stability was one of the major concerns. Apart from the fact that all necessary precautions were taken during design to prevent slope failure, the slope continued to fail in particular during the rainy season. The slope failure due to piping has been reported in various countries, including Tanzania. The landslide induced by piping in Tanzania has been reported in Mgeta in Morogoro region [2], along TAZARA railway [3] as well as in Kibauni-Southern Papermill, which transverse the same escarpment as Kihansi Dam Access road. It is hypothesized that most of the major slope failure along Udzungwas scarp is caused by piping which disturbs the soil equilibrium due to change in moisture content(increase) within the soil. Increase in moisture content leads to the deterioration of shear strength of soil to the extent that the shear strength along the slope exceeds the available shearing resistance of the soil. As far as the area is subjected to heavy rainfall every year, this piping erosion is active every year.

Further, it has been observed that due to the fact that the Udzungwa scarp is located on a very steep slope with an inclinometer in some location in excess of 30%. These slopes within the scarp are continuously disturbed by slow soil-creep under gravity as confirmed by the study of the orientation of the trees within the scarp which revealed that trees are leaning at different angles towards the sloping side (towards slope toe); suggesting that the tree roots are slowly and continuously pushed down towards the toe of the slope due to soil creep.

The erosion was found to be more noticeable in locations where the slope was found to be steeper or in a location where the land was bare. Thus, fast-moving water along soil slopes during the rainy season causes severe hydraulic scour and washes away slope-protective covers, leading to soil slope instability.

During rainfall, the soil softens, and cohesion of soil is lost, leading to a reduction of shear strength of the soil. Increase of moisture content to saturation of the soil, in particular, considering that the soil is of low-density and has high void ratio which promotes ingress of water, the soil can imbibe water equivalent to its liquid limit or more such that the soil offers little resistance to deformation. The shear strength of the soil at the liquid limit is estimated to be about 1.76 Mpa only suggesting that once the soil imbibes water to about its liquid limit, the shear strength of the soil is completely lost.

4.2 Tests on Soil Sampled from the Areas affected by Erosion and Landslide

Five soil samples were taken from the area affected by severe erosion and landslides and tested in the laboratory. The grading test results indicate that the soil has low clay content (typically less than 10%). The grain size distributions curves of soil sampled from the area affected by erosion are shown in Figure 8. The grading properties of these soils, expressed in terms of the coefficient of uniformity (C_u) and the coefficient of curvature (C_c), are shown in Table 1. Three samples out of five samples meet the requirements of the Unified Soil Classification System of well-graded soil, where a well-graded sandy soil should have both C_u >6 and C_c between 1 and 3. The grading properties indicate that these soils can be well-graded or poorly graded silty sand with a very low percentage of clay (Figures 3 and 8) suggesting that the soil becomes more resistant to erosion as clay content increases.

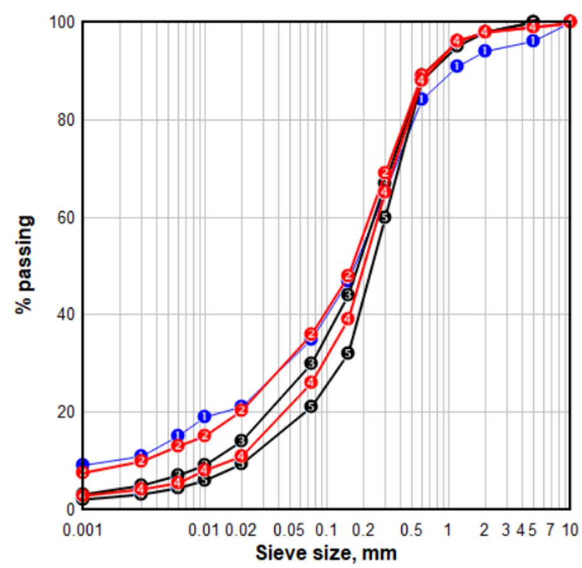

Figure 8; grading of the soil sample from locations with slope failure

Additionally, the physical characteristic indicates that these soils are generally characterized by low dry density, high void ratio, and low liquid limits. The summary of the physical characteristic results is shown in Table

2. The high void ratio in the soil is an indication that the soil possesses a very low inter-granular/effective pressure and low shear strength. The position of the soil on the A-Line plasticity chart is shown in Figure 4 from which it can be seen that the soil is of low plasticity, and based on the A-line classification chart, the soil can be classified as silty sand of low plasticity.

It has been reported [10] that an increase in the plasticity index and clay content is associated with increased resistance in erodability of the soil. The soil which exhibited slope failure is having both low plasticity index and low clay content. Utley and Wynn [10] evaluated wash processes for cohesive materials using a method that related critical shear stress, τ_{cr} (Pa), to several soil properties, including plasticity index. Critical shear stress was then used to determine a soil erodibility coefficient, k_d (cm^3/N-s). The established relationship is shown as equation 2, from which it can be seen that the critical shear stress is responsible for initiating the erosion; and erosion is a function of plasticity index of soil, i.e. as the plasticity index increases the critical shear stress of the soil also increases.

$$\tau_{cr} = 0.16(PI)^{0.84} \ldots Equation\ (2.1)$$

$$k_d = 0.2\tau_{cr} \ldots\ldots Equation\ (2.2)$$

K_d is an indicator of soil resistance to erosion. Mechanically, as plasticity index increases, cohesive forces between adjacent particles increase, requiring higher shear stresses to mobilize the grain, which results in increased resistance to erosion. The density of the soil also is known for improving the soil erodibility. But as it can be seen in Table 2, the soil available within the project area, which exhibited slope failure is having low dry in-situ density signifying that the soil can be easily eroded by fast-moving water after a rainfall. Based on erodibility classification of soil developed by Hanson [18,19], it can be seen that the soil available within the scarp falls within the band of moderately erodible soil, while the soil sampled from the location which exhibited slope failure is showing a high level of erodibility despite of the fact that all soil samples are falling within the same band of moderately erodable soil.

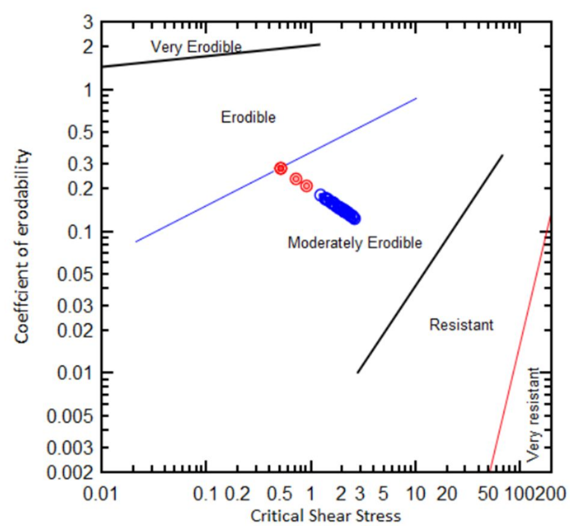

Figure 9: classification of erodability of Udzungwa scarp soil [18,19]

Table 1: Grading properties of soil sample

Sample Number	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	Coefficient of Uniformity	Coefficient of Curvature
1	0.0015	0.046	0.25	270	7.80
2	0.010	0.075	0.22	22	2.56
3	0.020	0.130	0.30	15	2.82
4	0.038	0.045	0.23	6.1	0.23
5	0.016	0.095	0.26	16.3	2.17

Table 2: Soil physical properties

Sample Number	Dry Density	Liquid Limit (%)	PI (%)	Activity	Void ratio	SG (g/cm^3)
1	1305 Kg/m^3	33	6	0.6	1.00	2.61
2	1228 Kg/m^3	33	4	1.0	1.14	2.63
3	1145 Kg/m^3	34	4	2.0	1.31	2.64
4	1092 Kg/m^3	35	8	0.9	1.40	2.62
5	1315 Kg/m^3	35	4	1.3	0.99	2.62

Table 3: Dispersion properties of soil sample

Sample number	Weight of soil sample	Clay content (%)	Moisture content (%)	Time for collapse (Seconds)
1	**2.5 g**	**10**	**13.0**	**29**
2	**2.5 g**	**4**	**12.4**	**19**
3	**2.5 g**	**2**	**11.8**	**13**
4	**2.5 g**	**9**	**14.8**	**24**
5	**2.5 g**	**3**	**5.9**	**15**

4.3 Dispersion properties

Due to the sloping topographical nature of the scarp, which promotes erosion, the soil available within the scarp is susceptible to dispersion. To ascertain the susceptibility of the soil structure to collapse upon saturation, a simple dispersion test, as suggested by Benites[7] was used. This test was carried out by dropping a 2.5 g of soil sample block into a cup containing 125 ml of distilled water and recording the time for the complete collapse. Dispersion tests were run in all five gathered samples; the summary of the result is shown in Table 3.

Albeit the fact that this simple dispersion (crumb) test did not conclusively provide evidence that the soil available within the scarp is dispersive, the following conclusions are drawn from the results shown in Table 3:

- The soil samples generally have a non-stable water structure. The dispersion time ranged from 13 to 29 seconds for tested soil samples.
- A tendency to increase in dispersion time as the clay content increases is noted.

The same conclusions were drawn by Masannat [7] who used the same simple dispersion test while studying the piping erosion in the Benson area, Arizona.

4.4 Mica in Soil

Residual soils developed from igneous rocks frequently contain large amounts of mica, which is considered to be detrimental for engineering use.

Various authors have reported the effect of mica in soil. The presence of mica in the soil increases porosity, compressibility, and reduces the shear strength of the soil. Therefore, the soil which contains mica is more susceptible to collapse, erosion and unstable in comparison to the non-micaceous soil under similar conditions.

Mica also has been reported to give artificially high liquid limit, increase in plastic limit, decrease in plasticity index, to reduce the degree of compaction of soil, decrease in dry density and increase in optimum moisture content [11][12][15][16][17].

The mica is very flexible and elastic, especially the white mica (muscovite). During compaction, the mica platelet bends easily and tends to return to its original shape due to the elastic rebound. This "springing action" tends to increase the void ratio with undesirable consequences for compacted layers (reduction in density), subsequently promoting ingress of water in the pavement. During the construction of Lower Kihansi Dam Access road, very micaceous silty sand was encountered along the alignment from Km 6-10. The presence of mica in the soil along this section gave a considerable problem during compaction due to the elasticity and flexibility of mica particles. Through on-site compaction trial, it was established the micaceous soil could be effectively compacted using sheep foot roller due to its kneading action. The vibratory drum roller was found not to be effective because its vibration promotes the springing action of the mica particle leading to an elastic rebound of the mica platelets. The vibratory tends to promote a "springing" action of mica platelets while the kneading action of sheep foot roller tends to embed the mica platelets particles within the soil matrix.

4.5 Collapsibility of Soil

Collapsing of the soil is caused by moisture content, which dissolves the weakly cementing minerals holding the soil particles together, leading to soil bond between the grain to break down. Collapsible soil is sensitive to moisture content and weakly held by water-soluble bonding minerals, which softens upon saturation. Such oil can be easily washed away with the overland flow, i.e., the soil is prone to erosion.

The crumb test conducted to assess soil dispersion soil behaviour indicates that the soil within the scarp is having a non-water stable structure, sensitive to moisture content, and is of low in-situ dry density. Because low dry density indicates a loose structure of the soil, the in-place dry density is a good parameter for the collapse prediction of soil. These characteristics suggest the soil available within Udzungwa scarp is likely to be collapsible.

In order to assess the collapsible potential of the soil, the soil was evaluated using methods developed by Holtz et al. [1961][20] and Moghadam [2006] [21], which the dry density of the soil is related to the liquid limit and dry density is related to percentage passing 0.075 mm sieve. The soil, when plotted on these charts, falls within the band of collapsible soil, suggesting that the soil available within the scarp is collapsible soil.

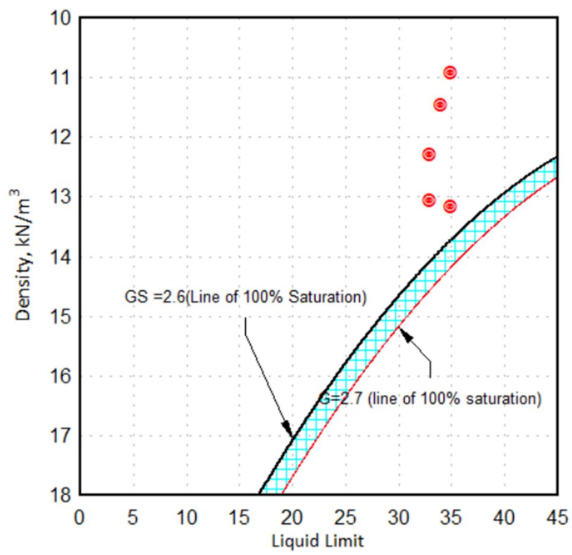

Figure 10: classification of collapse potential [20]

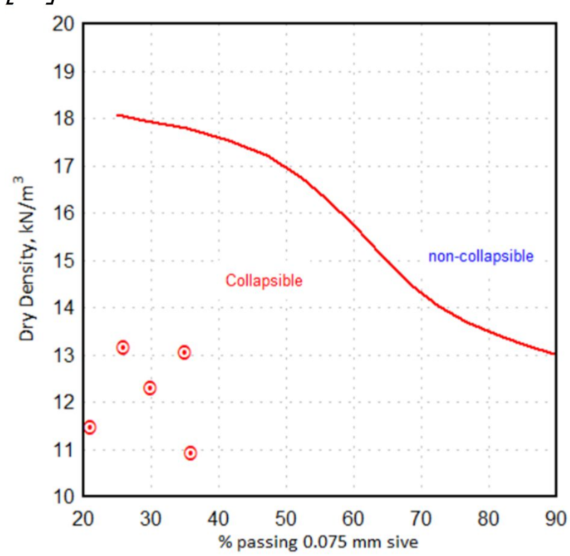

Figure 11: classification of collapse potential [21]

5.0 CONCLUSION

The soil along the Udzungwa scarp is divided into two main groups, namely non-transported soil (residual soil) and transported soil. The geotechnical properties of this soil, as well as the slope morphology, are responsible for the rain-induced slope failure along this scarp. From this study, the following can be concluded.

- The soil available within the Udzungwa scarp, in particular in the areas prone to landslide, is very erodible and collapsible silty sand or sandy silt with low plasticity, low clay content, and unstable upon saturation due to decrease in cohesion and shear strength of the soil.

- The soil erosion, as well as the slope failure along this scarp, is caused by uncontrollable factors like slope morphology, high rain intensity as well as gross properties of soil. The main cause of erosion is the concentrated surface runoff hence causing the water to flow through highly erodible and collapsible soil encountered along the Udzungwa scarp. Additionally, during the rainy season, slopes are under the action of water running down to its face and exert a downward drag, thus leading to erosion.
- The area along the Udzungwa scarp is suspected of comprising of pipe networks that cover a very large area. It is postulated that many erosion gullies within this area have been caused by the enlargement of oil pipe diameters to such extent that the overlying material collapsed into it. Additionally, the water movements within the soil (through a network of pipes) washes away the small particles (clay-like soil particles), which acts as a bonding agent leaving behind soil rich in silt, decreasing the inter-granular bond.
- All major slope failure and landslides along Udzungwa scarp are attributed to the existence of soil pipes, which disturbs the soil equilibrium after the increase of moisture content during rainfall, leading to a deterioration of shear strength of soil to the extent that the shear strength along the slope exceeds the available shearing resistance.
- The natural and man-made slope failure is due to the creep movement of soil under the gravity of the steeply sloping terrain whose lateral support has been removed by the cut. As far as the area is subjected to heavy rainfall every year, erosion, slope failure, and landslides are active every year. The amount of rainfall, as well as the rain intensity along this area, is directly connected to landslides and slope instability in the area.
- The slope failure is also aggravated by the presence of mica within the soil which inherently reduces the shear strength of the soil

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