Title: Geological mapping to assess social and environmental impact of possible slopes instabilities along the Karuma HPP reservoir, Uganda

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Introduction

The impounding of reservoirs can have major social and environmental impacts that are not necessarily limited to the flooded area but can in some cases also extend to the surrounding areas. Geological mapping of reservoirs is often done mainly to assess their water tightness or the presence of landslides that could affect the safety of the dam or the downstream population. To assess all social and environmental possible impacts, a more detailed mapping focusing for example on very small landslides or on water springs and taking into account the land usage can be necessary. The example of the Karuma dam located along the Nile River near Karuma village in Uganda is discussed in this paper.

The impounding-related water level increase in the Karuma reservoir is limited to a few meters but depending on the geological conditions even such small water level changes can affect the shore stability. In Karuma where many small settlements, living from agriculture, are found along the Nile shores, even small losses of land could strongly impact the local population.

For this reason, a detailed geological risk assessment along the reservoir shore was requested by Uganda Electricity Generation Company Limited (UEGCL) with the scope to define:

- Hazards and risk
- Need to buy additional land or to compensate for land losses
- Need for mitigations measures/monitoring systems

The results of the geological mapping focusing on Environmental and Social aspects were used for the development of a risk matrix allowing to identify possible risk areas, to focus attention on these areas during impounding and operation, and eventually, if needed, to carry out additional studies and/or compensate or mitigate social or environmental impacts caused by the impounding of the reservoir.

1. Background

The Karuma dam is located in northern Uganda along the Nile River in the near of the Karuma village. The Karuma HPP scheme consists of a concrete dam (Figure 1), 14 m high, an underground Powerhouse and an about 9 Km long tailrace tunnel. The Karuma HPP reservoir is about 60 Km long for a storage capacity of about 80 Million m^3.

The scheme will be operated as run-off river plant and the water level in the reservoir varies between 1028 m and 1030 m asl.

1.1 Scope of the assignment

The Scope of the assignment here presented was to assess the Reservoir slopes stability to define hazard and risks along the reservoir and eventually the necessity of remedial measures to mitigate the impact of possible failures. Considering, the extension of the area (More than 50 Km long reservoir) and its morphology, a flat plateau with limited rocks outcrops, the works did not focus on producing a complete geological map of the area but to produce typical morphological and geological profiles representative of the different situation observed along the reservoir shores. Based on these data an assessment of the risks of failures and of their possible impact has been made.

Fig. 1. View of the reservoir slopes immediately upstream of the Karuma dam.

1.2 Geography

The Project area is located in northern Uganda, along the Alberta Nile, at about 120-150 Km from the borders with Congo in the West and Sudan in the North. This area is characterized by plateau topography and overall flat terrains. The highest point is on the west coast of Lake Albert, at about El. 1900m, and the lowest point at the northern border of Uganda at about El. 750m. near of the dam ground elevation range between 960 m and 1075 m asl.

In the project area, the Nile valley strikes mainly NNW-SSE to N-S forming some large bends/meanders toward the end of the reservoir and the river width varies from tens to several hundred meters.

1.3 Geology

The project area is located on the Victoria Plate between the east and west branches of the East African Great Rift Valley in a vast plateau formed by Archaean rocks

The ground in the Project area is mainly composed of:

- Quaternary: eluvium and alluvium (2.6 myr to present)
- Proterozoic: Schists (460 – 2500 myr)
- Archean: gneiss, diorite, gabbro and granite (2500-4000 myr)

The eluvium (Laterites) cover most of the plateau area and is the result of in situ rock weathering. The laterites are made of a reddish ferruginous silty/clayey matrix, locally cemented, containing iron mottles, pisolites and nodules. In the river bed Alluvium, consisting of alluvial sand, silt and gravel, is found. Medium to coarse-grained alluvium covers the bottom of the river while in flood areas and swamps finer-grained alluvial sediments are found. Locally lacustrine deposits like silt and clay are also present.

The thickness of the overburden in the drilled boreholes ranges between 0 and 10 m with an average thickness of about 5 m. Generally, thin soil and weathering layers characterize the areas close to the river while moving away from the river bed and at higher elevations, the thickness of the weathered zone rapidly increases.

The main regional faults are associated with the Albertine Rift in the west (NE-SW direction) and the Aswa shear zone, in the NE, that strikes NW-SE (Figure 3)

No major faults are found within 25km from the dam site according to the Design study, while most of the faults found near the project area are related to the Albertine rift.

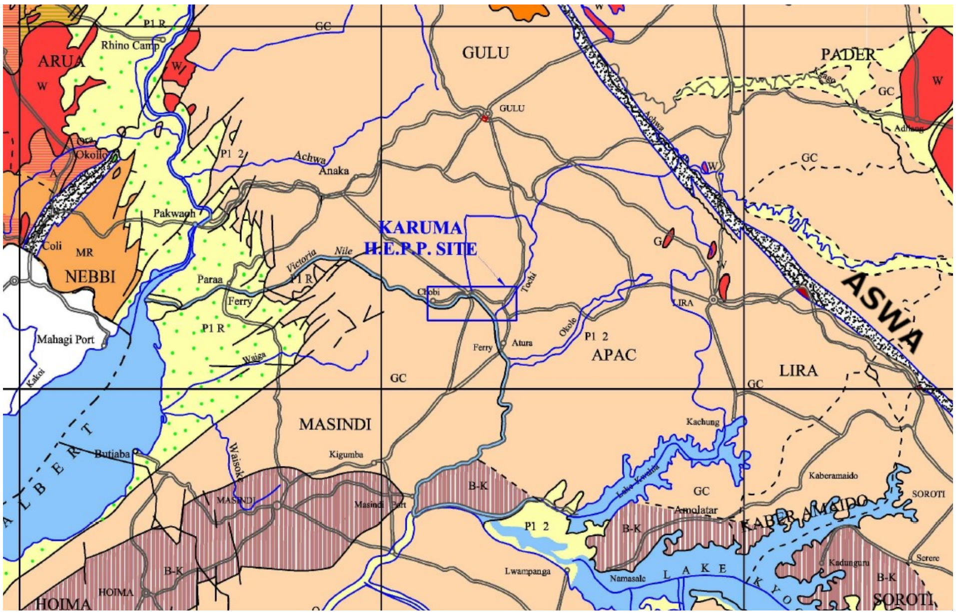

Fig. 2. Geological map of the region; GC undifferentiated Archean rocks; P1-2 Pleistocene.

2 Methodology

The work consisted of a desktop study followed by two weeks on-site to carry out the fieldwork.
Before the fieldwork the following documents were provided:

- Geological Design Reports
- As Build drawings Dam, Powerhouse and Tunnels
- Reservoir survey including topographic sections of the reservoir

2.1 Desktop Work

After analyzing all provided documentation a first recognition of the reservoir close to the dam was done to understand access conditions to properly organize the work. Representatives of the local community were involved during the planning phase and then during fieldwork.
The data analysis evidenced that the reservoir topographical map did not provide valid support to orient in the field and to map, because this map did not cover the areas outside of the reservoir perimeter. This together with the very flat and monotonous morphology of the plateau surrounding the reservoir would have made it very difficult to orient in the field and to find suitable paths to reach the reservoir.
Mapping moving always along the reservoir shores by foot or by boat was then excluded because of the following difficulties:

- Very long distances to cover, difficulties to orient and walk due to the vegetation and the presence of swamps
- Fences for livestock are not easy to cross and Absence of continuous paths
- Rapids that prevent the safe use of small boats (only wooded paddle boats are used in the area)

Given these conditions satellite photographs and maps available online have been used to look for access to the shores and to plan the work. Carriage roads and paths were identified to optimally plan the fieldwork. The result of this work is visible in Figure 4 where the main access roads and paths to the reservoir are highlighted.

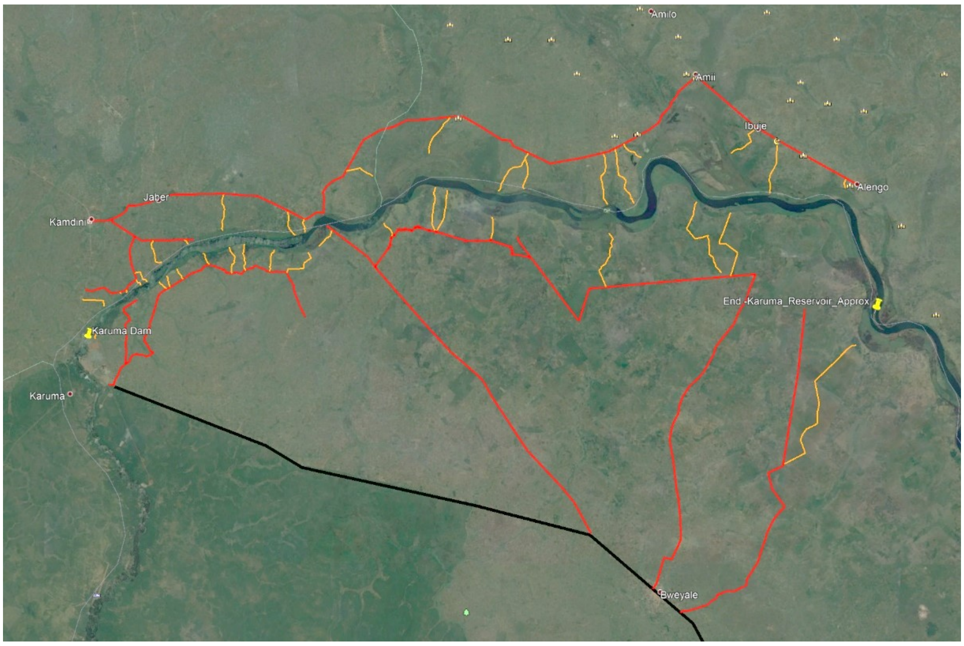

Fig. 3. Access roads to the Reservoir located on satellite photographs and online maps – Black: Main road; Red: Possible drivable assess roads; Orange; possible access paths.

The traces of these roads and paths were then exported to the smartphone to be used during mapping as help to orient in the field.

The area to be inspected was then tentatively divided into six areas to be covered during the two weeks available for the mapping, based on the reservoir size and available access. Area close to the dam was given more time in the program because of the morphology of the area (higher slopes) and the expected higher water level increase in the reservoir (about 2 m). During the fieldwork tracks of the drive/walk paths were recorded using field GPS. Information about the morphology of the area, vegetation cover, presence of outcrops, the nature of outcropping soils and rocks and the land usage were noted and documented in the field book and by photographs.

2.2 Field Work

Based on the results of the mapping the seven sections present similar characteristics were recognized (Table 1). The absolute height of the slopes could not be measured exactly due to the lack of reference points and The given values are estimated and when possible cross-checked with the provided topographic sections.

During the field mapping detailed information on morphological and geological conditions was gathered at 37 selected locations and during walks along paths and from panoramic points.

A representative of the local communities accompanied the surveys on a daily basis and local people were hired as guides in the most difficult to access areas.

Location	**Distance from Dam**	**Morphology**	**Geology**	**Stops**
Section 1 - Left bank	0+000m to 4+500m	High steep slope (15-25m) with subvertical scarp at the top	Laterites, Top layer generally well cemented, locally bedrock at the base locally rock	Stops 1, 2, 3, 34, 35, 36 and 37
Section 2 - Left bank	4+500m to 10+000m	High Slope (</= 10m high) with generally no scarp at the top	Laterites, Top layer generally well cemented, locally bedrock at the base	Stops 6 to 11
Section 3 - Left bank	10+000m to 35+000m	Very flat slope (Max 1 – 5 m high) or large marshes covered by papyrus	Laterite or top soil	Stops 4, 5, 12, 13 and 14
Section 4 - Right bank	0+000m to 2+500m	Low slope (4-5m) with gentle morphology	Bedrock, Laterites and top soil,	Stops 15 to 19
Section5 - Right bank	2+500m to 5+000m	High steep Slope (15-20m high) with generally small or no scarp at the top	Laterites, Top layer generally well cemented, locally bedrock at the base	Stops 20, 21, 22 and 28
Section6 - Right bank	5+000m to 10+000m	Slope (<10m high) with generally no scarp at the top	Laterites, Top layer generally well cemented, locally bedrock at the base	Stops 23 to 27
Section 7 -	10+000m to	Very flat slope (Max 1 – 5 m high)	Laterite or top soil	Stops 29 to 33,

Right bank	35+000m	or large marshes covered by papyrus		

Table. 1. Area with similar morphological and geological characteristic identified during the desktop study and related stops made during survey

Considering the scope of work, and the observed geological/morphological conditions, fieldwork mainly focused on the first 10 Km of the reservoir but locations about 35-40 Km upstream of the dam site were reached during the fieldwork. The collected data were used to prepare typical geological profiles that can allow to highlight the possible risk of failure along the slope for each homogeneous zone.

3. Results and analysis of the survey

3.1 Local Geological Conditions

The orientation of the Nile in the reservoir area is first roughly N-S and does not follow any major regional tectonic contacts that instead strike NE-SW or NW-SE. Considering that the river valley is here mainly cut through soil and highly to completely weathered rocks the lithologies and the structures of the bedrocks are considered to have no major influence on the orientation of this nearly straight section of the river. The large bend observed at Stop 29 is instead probably due to locally raised bedrock, due to folding or faulting, as suggested also by the presence in this area of small hills close to the river.

The seven (7) sections with similar morphological and geological characteristics previously defied were, based on the analysis of the field data, grouped in four (4) homogenous zones with similar characteristics (Table 2).

The main characteristics will be described in the next chapters.

Homogeneous Zone	**Location**	**Distance from Dam**	**Morphology**	**Geology**
1	*Section 1 - Left bank*	*0+000m to 4+500m*	*High steep slope (15-25m) with often a subvertical scarp at the top*	*5-10 m laterites, Top layer generally well cemented,*
	Section5 - Right bank	*2+500m to 5+000m*		
2	*Section 4 -Right bank*	*0+000m to 2+500m*	*Low slope (4-5m) with gentle morphology*	*Mainly Bedrock mainly covered by alluvial sediments and locally also by laterite*
3	*Section 2 - Left bank*	*4+500m to 10+000m*	*High Slope (</= 10m high) with generally no scarp at the top*	*5-10 m laterites, top layer generally well cemented,*
	Section6 - Right bank	*5+000m to 10+000m*		
4	*Sections 3 and 7 – Right and Left bank*	*10+000m to 35+000m*	*Very flat slope (Max 1 – 5 m high) or large marshes covered by papyrus*	*Mainly laterites, top layer generally well cemented,*

Table. 2. Morphological and geological homogenous zones defined along the Karuma reservoir

Observations made in the field indicate that an indurated layer is often present at the top of the laterite that is responsible of the morphology of the area, characterized by a plateau with a generally very flat surface. Below this layer outcrops were very rare with nodular laterite with clast rich layers and clay layers locally observed along the river slopes.

As the scope of the assignment was to define risk areas no test pits or other investigations to characterize the underground in detail could be carried out. For this reason, the stratigraphy at the different locations and the groundwater level are not known in detail as well as the nature of the material present in the 1025m 1030 m El. in contact with the reservoir water.

The own observations were then combined with the data from the available geological reports to define typical geological sections for the area close to the dam site.

Zones 1 & 2

- Top soil (30-40 cm)
- Indurated (loose in Zone 2) laterite with nodules and clasts and a silty/clayey matrix (1-5 m)
- Laterite with nodules and clasts and a silty/clayey matrix with lenses/Layers of silty-clay (1 - 9 m).
- Completely weathered metamorphic rocks; Gneiss and Gabbro (3 m or more)
- Highly weathered metamorphic rocks; Gneiss and Gabbro (3 m or more).

In both zones the described alluvial grayish sandy soil probably rests in unconformity on the different layers described above both along the slopes (recent alluvium) and on the plateau (old alluvium).

For areas located farther away from the dam the limited number of outcrops does not allow to produce sections and due to the morphology of the area only the lateritic soil or the alluvial soils are generally found along the reservoir slopes that here are only a few meters high. Based on the observation made it can indeed be assumed that geological conditions are mainly similar to the one described for Zones 1 and Zone 2.

3.2 Description and analysis of homogeneous zones

Zone 1: In this zone slopes are generally 15 m to 25 m high, subvertical at the top where the indurated laterite is found and becomes flatter below this hard layer. The inclination of the lower part of the slopes ranges between 35°-45° and 20°-25° and the overall width, from the plateau to the river, is between about 50 m to about 100 m.

The presence of laterite at the water level is excluded because the maximum thickness of the laterite is about 10 m much lower than the height slopes and mainly weathered rocks are expected to form the slope at the reservoir elevation (1028-1030 m asl). This means that the lower and flatter part of the slope is mainly stable but erodible, while the central and upper part of the slope is generally steeper than what the properties of the material would allow because of the presence of the top indurated layer.

Erosion at the base of the slope could induce failures that then propagate toward the cliff potentially also affecting the plateau.

Fig. 4. Left: Stops 34 - 36 Example of wide slope that flatten down toward the base. Right: Stop 2; View from the top of the slope of fallen blocks and tilted blocks

The land close to the slope is here used as a pasture for cattle. Some huts are also present at about 100 m from the slopes (Stop 1) while new buildings were observed at about 20 – 50 m from the cliff including an hospital.

Along the slops itself some small agricultural fields were observed too.

Zone 2: This zone is characterized by gentle slopes (15°-25°) that generally reach an elevation of about 4 to 5 m at about 15-20m from the shore and then becomes flatter to reach an elevation of about 20 above water level hundred or more meters away from the shore.

Only few outcrops could be found here and based on the morphology of the area it can be assumed that here only locally cemented laterite is found. Considering the morphology and the nature of the underground only small failures are expected here, limited to the sandy alluvial layer that covers the lower part of the slope.

Agriculture is diffuse along the while villages are located above the slope on the plateau far away from the river bank.

Zone 3: Here the height of the slopes ranges between 8 -10 m close to the dam and about 4-5 m toward the upstream. Generally, the slope presents the same geometry described for Zone 1 with often the presence of a small cliff on top formed by indurated laterites and a lower part of the slope that is first still steep (35°-45°) and then becomes gently inclined (25° or less) toward the base.

Loose or semi-indurated lateritic soil is expected to be found at most locations at the base of the slope, with the local presence of bedrock mainly completely to highly weathered.

Given these conditions small failures are possible but should be of very limited extension. The development of larger failures that could reach the top of the slope is very unlucky but cannot be completely excluded.

Locally the slope is used for agriculture (banana and other fruit trees) while the shore is covered by papyrus and reeds. A water spring used by locals was located at the base of the slope (Figure 6) and along the edge of the plateau several small villages or single houses are found and most of the land is used for agriculture.

Fig. 6. Stop 11 – Location of the water spring (Red arrow).

Zone 4: This section of the river is characterized by very flat slopes that rise gently only a few meters out of the river or by flat marshes covered by reed and papyrus. Along the paths followed to reach the river nodular reddish indurated laterite was observed covered by sandy alluvial soil. Given the morphology and the nature of the underground only very small failures are expected here.

4. Analysis of results

The fieldwork evidenced that the slopes along the reservoir are mainly in natural conditions. These slopes, especially the high ones are characterized by ongoing erosion and failures as described above (Figure 6). The erosion and instability observed at the top of the slopes in Zone 1 are part of a natural erosion process that will continue independently of the presence of the reservoir.

Concerning the impact of the reservoir on the slopes stability it is important to consider that the increase in water level is very limited and within the range of large floods that already shaped the slopes in the past. For this reason, the risks of failure related to erosion caused by the reservoir water are considered relatively low for the Karuma reservoir and limited in extension. This also considering that the reservoir will reduce the dynamic of the river, with the water flowing slower than before especially during floods.

On the other side the higher water level over a long period could in some areas induce a deeper saturation of the slopes causing weakening of the material and leading to some instabilities.

This process could induce relatively large instabilities, that reach the top of the slope especially close to the dam where high and steep slopes are locally present (Zone 1 and 3). These slopes, as mentioned above are not stable and already undergoing erosion. The upper part of these slopes is often steep, and in general much steeper than the material properties would allow. This is due to the presence of a layer of well-cemented laterites at the top of the slopes. Failure along the reservoir shores could then propagate to the upper part of the slope and reach the plateau where also buildings are present.

The risks this will happen are estimated to be low because where the base of the slope is steep, strong rocks have been observed. In other areas, where weak material is probably present the base of the slopes is completely covered by vegetation and flatter than friction angles given for laterite and completely weather rocks in the Design documents.

On the base of the collected data, the observations made in the field, and the consideration above, the hazard and risks and the possible impact of slope failures in the four homogeneous zones have been defined. The results of this analysis are summarized in Table 3.

Zone	Hazard	Risks	Risk level	Impact	Initial remedial measures
1	Localized erosion or small failure along the slope	Loss small agricultural areas	2-3	Low	Monitoring
1	Slope failures that can reach the top of the slope	Loss agricultural areas; loss of buildings	2	Low in case no buildings are present.	Monitoring
1	Slope failures that can reach the top of the slope	Loss agricultural areas; loss of buildings	2	Moderate in case building are present (Stops 1, 2 and 36)	Monitoring

1	Slope failures that can reach the top of the slope	Loss agricultural areas; loss of buildings	2	High for stops 3, 34 and 35 where a hospital is present close to the cliff	Monitoring, Evaluation further investigations and eventually of further remedial measures
2	Localized erosion or small failure along the slope	Loss agricultural areas	2-3	Low to moderate	Monitoring
2	Slope failures	Loss of water spring (Stop 11)	2	Moderate to high for the water spring	Monitoring, Further investigation to better define elevation of the spring and risks of erosion
3	Localized erosion or small failure along the slope	Loss small agricultural area	2-3	Low	Monitoring
3	Slope failures that can reach the top of the slope	Loss agricultural areas; loss of buildings	2	Low in case no buildings are present.	Monitoring
3	Slope failures that can reach the top of the slope	Loss agricultural areas;	2 -3	Low for the agricultural area	Monitoring
4	Erosion along the slopes	Loss agricultural areas;	2	Low	Monitoring
4	Erosion along the slopes	Loss buildings	2	Moderate	Monitoring

Table. 3. Summary of hazards and risks defined for the Karuma reservoir, their possible impact and remedial measures

2. Conclusions

A geological mapping focusing on Social and Environmental aspects and the development of a risk matrix is an important tool to allow to identify possible risk areas, focus attention on these areas during impounding and operation, and eventually, if needed, compensate or mitigate social or environmental impacts caused by the impounding of the reservoir.
Despite this geological mapping of reservoirs often focus only on water tightness or the presence of large landslides that could affect the safety of the dam or the downstream population.
The example of Karuma HPP, shows how despite the very favourable topographical and geological conditions, which generally guarantee good slope stability, the study allowed to identify risk areas along the reservoir shores. Knowledge of these risks can allow monitoring of the situation, the definition of more accurate studies and the identification of appropriate preventive and/or compensatory measures.

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