Underwater Investigation and Analysis of Upstream Face for a Built 40 years’ and 6 km Long Embankment Dam in Africa

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Abstract. The world’s hydropower has experienced considerable development. With the coming of the post hydropower era [1], the business of new projects will gradually decrease, and meanwhile, the business of hydropower station renovation and dam maintenance will gradually increase. This paper introduces the methodology and the finding of the underwater investigation, analyses the upstream face stability and recommends solutions of rehabilitation for a built 40 years’ and 6 km long embankment dam in Africa, aiming to provide a reference for similar projects of dam maintenance.

1. Background
The world’s hydropower has experienced considerable development. With the coming of the post hydropower era [1], the business of new projects will gradually decrease, and meanwhile, the business of hydropower station renovation and dam maintenance will gradually increase [2].

An embankment dam in Africa was started in 1977 and completed in 1982, which is composed of the east and west dykes with a total length of 6 km and the maximum dam height of 18 m approximately. The typical section of the embankment dam consists of 1.5 m thick coarse rock-fill, 0.9 m thick fine rock-fill, 0.9 m thick sand filter, impervious material, and 0.9 m thick fine rock-fill from upstream to downstream. Both the slope of upstream and downstream are 1:2. After decades of year’s operation, some of the upstream rock-fill of the dam had collapsed, therefore the owner decided to carry out an underwater investigation and analysis of the dam upstream face.

![Figure 1. Typical section of the dam.](image)
2. Underwater Investigation

2.1 Choice of the Methodology
Currently, underwater investigation equipment includes side sweep sonar, shallow profiler, 3D panoramic imaging sonar system, and multi-beam echo sounder, etc. [3-4]. The side sweep sonar can acquire 2D image information underwater, but not accurate position coordinate data. The shallow profiler is a device for detecting the structure of shallow underwater formations, and is not suitable for surface topography. Although the 3D panoramic imaging sonar system can acquire images and 3D structural information, it needs to build many fixed working platforms on the water surface. Therefore, the equipment mentioned above cannot meet the requirements of this project.

Multi-beam echo sounder is a complex combination system with multiple sensors. It is a modern signal processing technology, high-performance computer technology, high-resolution display technology, high-precision navigation and positioning technology, digital sensor technology and other related high technology. Multi-beam echo sounder can greatly improve the efficiency of underwater topographic survey. For the traditional single beam sounder, each measurement can only obtain a depth value below the vertical direction of the measurement ship, while multi-beam sounder can obtain the depth value of multiple measurement points in a strip coverage area. The multi-beam echo sounder has the advantages of large measuring range, fast measuring speed, high precision and high efficiency. It extends the sounding technology from points and lines to the surface [3-7]. Therefore, the multi-beam measurement is the optimal method of measurement for this project, and meanwhile, a ROV (remote operative vehicle) is used to review the result of multi-beam.

2.2 Observations and Findings
According to the investigation results, a 3D model of the upstream surface of the embankment dam is generated. The 3D model and the data of multi-beam echo sounder are used to judge the condition of the upstream surface, and to select the potentially dangerous sections used for analysis. The 3D model, typical measured sections and photos taken by ROV are shown in Figure 2~7.

The conditions of the upstream face are described as below:
- A step occurs at some parts of the west dyke upstream surface under the water. The main area locates at CH 1+710 m ~ CH 1+990 m and CH 1+490~550 m, the width of the step is

![Figure 2. 3D model and typical measured sections of the upstream surface.](image-url)
generally lower than 2 m. The typical measured section of this area is section 1 shown in Figure 3.

- Rock-fill collapse occurs at some parts of the west dyke upstream surface above the water. The rock-fill collapse mainly occurs at the area of coarse rock-fill part and locates at CH 0+860 m ~ CH 1+990 m. The rock-fill collapse is discontinuous and distributes along the dyke. The width of each collapse area is about 2~6 m. The rock-fill collapse causes the upstream slope to form a steep slope above the water. The rock-fill collapse’s vertical depth of CH 1+260 m ~ CH 1+710 m is more than 40 cm above the water, the typical section of this area is section 2 shown in Figure 4. The rock-fill collapse’s vertical depth of CH 0+860 m ~ CH 1+260 m and CH 1+710 m ~ CH 1+990 m is less than 40 cm above the water, the typical section of this area is section 3 shown in Figure 5.

- The upstream surface of the east dyke is better. There are only slight rock-fill collapses above the water, the distribution of the rock-fill collapse is scattered, and the width of the rock-fill collapse are less than 3 m. The typical section of this area is section 4 shown in Figure 6.

Figure 3. Measured Section (Section 1).

Figure 4. Measured Section (Section 2).

Figure 5. Measured Section (Section 3)

Figure 6. Measured Section (Section 4).

(a) West dyke above water.

(b) West dyke under water.

(c) East dyke above water.

(d) East dyke under water.

Figure 7. Typical photos of upstream surface above/under water.
3. Stability Analysis

3.1. Analysis Assumptions

3.1.1. Analysis model and material parameters. The stability analysis of this paper uses the Morgenstern-Price method which considers the inter-strip force based on the rigid body limit equilibrium. By simulating the dam body wetting line, the effective stress method is used to automatically search for the minimum safety factor and the corresponding slip surface position. The analysis model and material parameters are shown in Figure 8 and Table 1.

![Analysis model](image)

Figure 8. Analysis model.

| Material          | $\gamma$ (kN/m$^3$) | Effective stress |
|-------------------|----------------------|------------------|
| Rock-fill         | 21.2                 | 0                |
| Sand filter       | 19.6                 | 0                |
| Impervious fill   | 18.8                 | 13.8             |
| Foundation silt   | 18.0                 | 6.9              |

3.1.2. Analysis conditions. This paper takes 5 conditions as follow into consideration:

- Normal operating level (stable seepage) condition a: Upstream water level 14.75 m, downstream water level 3.75 m.
- Normal operating level + seismic load conditions b: Upstream water level 14.75 m, downstream water level 3.75 m, horizontal seismic acceleration 0.16 g.
- Design flood conditions c: Upstream water level 15.3 m, downstream water level 6.2 m.
- Water level rapid drawdown condition d: The upstream water level drops from Maximum operating level 17.68 m to Normal operating level 14.75 m.
- Water level rapid drawdown condition e: The upstream water level drops from Normal operating level 14.75 m to Minimum operating level 14.30 m.

3.2. Stability Analysis Result

According to the investigation of upstream surface for the dam, 4 typical sections are selected for calculation, the location of the sections are shown as Figure 2 and the result are shown as Table 2 and Figure 9.

For the section 1 with a step below the water surface, the safety factor of each condition can meet the USBR (Unit State Department of the Interior Bureau of Reclamation) requirements [8]. The step below the water surface does not have obvious impact on the stability of the upstream. For the section 2 with obvious upstream rock-fill collapse, the safety factor of all the conditions cannot meet the USBR requirements. For the section 3 and 4 with slight rock-fill collapse, the safety factor of each condition can still meet the USBR requirements.
Table 2. Upstream slope safety factor of typical sections.

| Section No. | Condition | Calculation Factor | Allowable Value of USBR | Calculation Factor / Allowable Value | Status | Safe / Dange |
|-------------|-----------|--------------------|--------------------------|-------------------------------------|--------|--------------|
|             |           |                    |                          |                                     |        |              |
|             | a         | 1.67               | 1.50                     | 1.11                                | S      |              |
|             | b         | 1.14               | /                        | /                                   | S      |              |
| Section 1   | c         | 1.76               | 1.20                     | 1.47                                | S      |              |
|             | d         | 1.63               | 1.20                     | 1.36                                | S      |              |
|             | e         | 1.63               | 1.30                     | 1.25                                | S      |              |
|             |           |                    |                          |                                     |        |              |
|             | a         | 1.03               | 1.50                     | 0.69                                | D      |              |
|             | b         | 0.85               | /                        | /                                   | D      |              |
| Section 2   | c         | 1.03               | 1.20                     | 0.86                                | D      |              |
|             | d         | 1.03               | 1.20                     | 0.86                                | D      |              |
|             | e         | 1.03               | 1.30                     | 0.79                                | D      |              |
|             |           |                    |                          |                                     |        |              |
|             | a         | 1.54               | 1.50                     | 1.03                                | S      |              |
|             | b         | 1.07               | /                        | /                                   | S      |              |
| Section 3   | c         | 1.54               | 1.20                     | 1.28                                | S      |              |
|             | d         | 1.52               | 1.20                     | 1.27                                | S      |              |
|             | e         | 1.52               | 1.30                     | 1.17                                | S      |              |
|             |           |                    |                          |                                     |        |              |
|             | a         | 1.56               | 1.50                     | 1.04                                | S      |              |
|             | b         | 1.08               | /                        | /                                   | S      |              |
| Section 4   | c         | 1.67               | 1.20                     | 1.39                                | S      |              |
|             | d         | 1.55               | 1.20                     | 1.29                                | S      |              |
|             | e         | 1.55               | 1.30                     | 1.19                                | S      |              |

Figure 9. Analysis result of typical conditions (normal operating level).
3.3. Sensitivity Analysis
To assess the stability of the upstream face, this paper analyses the safety factor when the shear strength of the filling material reduces. When the shear strength of the filling material reduces 5% of the original value, the safety factor of the upstream slope in the normal operating condition can meet the requirements of USBR. When the shear strength of the dyke filling material reduces 30% of the original value, the safety factor of the upstream slope in the normal operating condition will be lower than 1.0.

In the previous analysis, the most dangerous sliding arc is in the rock-fill area and the minimum depth of sliding arc is 1 m, however, when the depth of sliding arc increases, the most dangerous sliding arc will change. Therefore, the minimum depth of sliding arc as 4 m is chosen, which is just a little larger than the total depth of rock-fill and sand filter of upstream. The analysis indicates that when the shear strength of the dyke material reduces 27% of original value, the safety factor of upstream slope in the normal operating condition can meet the USBR requirements. When the shear strength of the dyke filling material reduces 51% of the original value, the safety factor of upstream slope in the normal operating condition will be lower than 1.0.

The impact of backfilling material shear strength reduction and depth of sliding arc are shown in Table 3 below, and it can be concluded that the upstream surface stability of dyke has a large safety margin and the rock-fill part is easier to slide than the impervious part.

| Safety factor                                    | 1 m depth sliding arc | 4 m depth sliding arc |
|-------------------------------------------------|-----------------------|-----------------------|
| Meet the requirements of USBR                   | <5%                   | <27%                  |
| Lower than the requirements of USBR, but more than 1.0 | 5%~30%               | 27%~51%               |
| Lower than 1.0                                  | >30%                  | >51%                  |

4. Solutions of Rehabilitation

4.1. The Cause(s) of the Rock-fill Collapse of Upstream Face
According to the result of the underwater investigation and stability analysis above, it can be concluded that the rock-fill collapse mainly occurs at some parts of coarse rock-fill part on the surface and the upstream slope stability of the original dam can meet the design requirements and has a certain safety margin. Considering that there’s no other accident or reason was reported, therefore it’s judged that the effect of wave action in long term operation period is the main cause of the rock-fill collapse of upstream face.

The surface wind speed is generally with inland speed averaging about 8~15 km/h, but maximum wind speed of 106 km/h have been recorded at the coast [9]. In addition, the length of the dam is about 6 km, the water face of the reservoir is wide, which is conducive to the formation of waves. The winds are generally west to south-westerly or south-westerly throughout the year, which explains why the rock-fill collapse obviously at the west dyke but not the easy dyke.

4.2. Rehabilitation of Upstream Face
For the upstream of west dyke located at CH 0+860 m ~ CH 1+990 m, the rock-fill collapse area is recommended to backfilled with sack gabion or coarse rock-fill covered by stone masonry to decrease the impact of wave action.

For the area with construction foundation above water, coarse rock-fill covered by stone masonry is recommended. The stone masonry has the advantage of strong cohesiveness and better out looking than the coarse rock-fill. With the protection of stone masonry, the wave brushing to the rock-fill and sand filter can be effectively resisted [10].
The sack gabion has a favourable adaptability to the irregular shape and operability for underwater construction. The rock-fill in the sack gabion will not be brushed easily. For the area without construction foundation above water surface or underwater, the sack gabion can automatically adapt to foundation deformation [11], which is a better choice for rehabilitation.

Figure 10. Photo of stone masonry.  Figure 11. Photo of sack gabion.

5. Conclusions
This paper chooses multi-beam echo sounder combined remote operative vehicle to investigate the condition of the upstream face for a built 40 years’ and 6 km long embankment dam in Africa and get the shape of rock-fill collapse for the upstream face. According to the analysis of the shape, stability and other information of the dam, it is judged that the effect of wave action in long term operation period is the main cause of the rock-fill collapse and backfilling with sack gabion or coarse rock-fill covered by stone masonry is recommended for rehabilitation.

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