Solutions for the stabilization of the left bank slope in Salvajina hydroelectric power plant.

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Abstract

The Salvajina hydroelectric power plant (HPP) is located in the municipality of Suárez, Cauca (Colombia). This HPP has been limited in its energy production due to absence of an operational spillway. This problem was originated during the construction process when the spillway discharge test generated a large-scale mass movement (approximately 60 000 m^2) on the left bank slope and an undercutting process around 20 m high in the discharge channel. Currently, the mass movement is in a state of limit equilibrium, requiring extensive repairs and stabilization works in order to guarantee a proper operation for the spillway. Therefore, the objective of this article is to present the analysis of possible solutions for the stabilization of the left bank slope and thus enable the operation of discharge channel, which in consequence will allow an optimized operation of the hydroelectric plant.

1 INTRODUCTION

The Salvajina hydroelectric power plant (HPP) is located in the municipality of Suárez, department of Cauca, Colombia. It was originally conceived as a multipurpose project for river Cauca flow regulation and hydropower generation.

The main elements of the power plant are the dam, the generation units (power house), the discharge tunnel and the spillway channel. The latter has not been used in the last three decades since the reservoir levels have never reached their maximum. [Celsia (s.f)]

Due to the extreme climatic changes of the last decades it is assumed that the probability of extreme rainfall events in the catchment area is systematically increasing. In consequence, it is expected that in medium term time scenario, the reservoir levels will be high enough to require the use of the spillway structure.

Consequently, it is necessary to improve the stability conditions of the left bank slope where the spillway channel is located, in order to mitigate negative consequences of a possible reactivation of the landslide.

To improve the stability conditions, two alternatives are presented. The first one is geometric reconfiguration of the slope through cuts and berms accompanied by support elements. The second alternative is the construction of a robust anchored wall made by a line of piles connected through a head beam. Both alternatives must be complemented by a surface and subsurface drainage system for depleting the water table on the slope.

Finally, a presentation of the advantages and disadvantages of each alternative is presented.

2 BACKGROUND

The Salvajina HPP is located in the municipality of Suárez, department of Cauca, Colombia. It was projected and constructed under the management of the Autonomous Regional Corporation of the Cauca River Valley –CVC- between 1981 and 1985 (Figure 1). The project was designed as a multipurpose reservoir for controlling river Cauca discharges and also generate electricity with an installed capacity of 285 MW.

The main components of the HPP are the reservoir, the dam, the discharge tunnel and the spillway with a discharge channel that was damaged by the left bank landslide occurred during the discharge test 30 years ago approximately.

Figure 1. Localization of Salvajina hydroelectric power plant.

At the time of design and construction of the project an area of instability was identified on the left bank of the discharge channel. This area is composed of alluvial deposits and unconsolidated colluviums with an approximate thickness of 30 m, with the water table close to surficial. There is also a presence of carbonated lutite rocks of very poor geomechanical conditions, which in some cases are dipped towards the slope which is clearly unfavorable to the stability of the left bank in which the discharge channel is located. These geological units have a complex morphology due to its steep slopes and rock massifs with a high degree of fracturing.

During the initial discharge test conducted on the spillway channel, an undercutting process greater than 20 m high occurred. The final third of the channel where strangulated by a mass movement of considerable magnitude and consequently the spillway never came to be able to operate.

Although during the time of operation of the HPP, there has been no need to put the spillway into operation, there is an increasing probability of intense rainy seasons in the future, which makes it necessary to release volumes of water from the reservoir through this structure, and, thus, there is a a risk of environmental, social, technical and economic effects due to the possible reactivation of the mass movement of the left slope.

Therefore, in order to guarantee a proper operation of the spillway it is necessary that the left bank slope be stabilized and then mitigate the risks associated with the possible reactivation of the landslide.

3 CURRENT STABILITY CONDITION

To assess the stability conditions of the slope, it is established that the most representative section is the one that passes through the axis of the mass movement, additionally a geotechnical characterization of the materials involved based on the information obtained from the existing exploration records was carried out. Table 1 shows the parameters of the materials involved in the study which are presented in the geological profile of Figure 2. Also, as a result of the explorations on site, it is established that the water table is very superficial, which causes the reduction of the soil resistance. [Suárez J, (1998)].

Table 1. Geomechanical parameters of materials

Material	Υ (kN/m^3)	C (kPa)	Φ (º)	GSI	σ_{ci} (kPa)	m_i
(QII)	19	10	22			
(Qd)	18	25	22			
(Qfv)	21	80	21			
(Qc)	19	23	25			
(Qal)	17	5	28			
(III)				25	20000	6
(II)				40	20000	6
(Ngi)					60000	

After performing a stability analysis which shows two potential failure surfaces with safety factors of 1.0 and 1.1, it is concluded that the static stability condition of the left bank slope is critical and then considered of likely to be reactivated. Figure 2 shows the stability analysis of the most representative section of the slope.

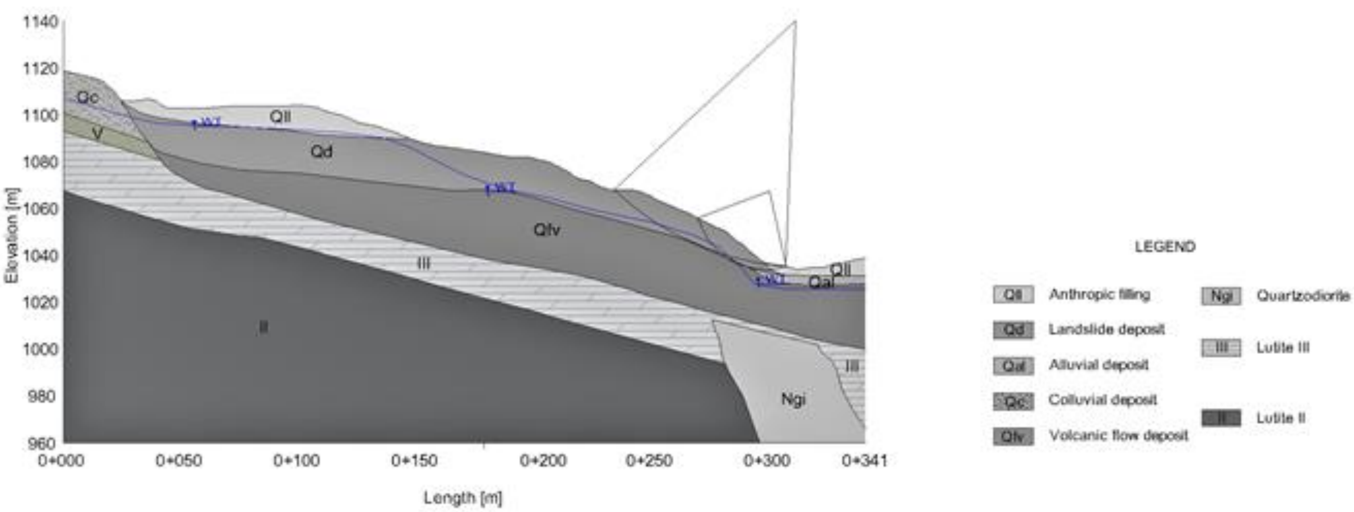

Figure 2. Slope stability analysis. Safety Factor 1,0 and 1,1.

The failure surfaces are found in the lower portion of the hillside where the slopes are steeper, and the water table is more superficial. These surfaces are located between the contact of the colluvium deposit (Qd) and the volcanic flow deposit (Qfv), where residual resistance parameters are considered due to the presence of a weakness zone.

For that reason, the imminent equilibrium condition can be affected by any modification that is made on the slope, and, thus, in order to rehabilitate the operation of the spillway discharge channel, stabilization works must be carried out.

4 POSSIBLE SOLUTIONS

Based on the current conditions of the slope, two possible solutions are considered. Regardless of the chosen alternative, there must be a complementary water control system, consisting of surface drainage, subsurface drainage and a soil-bentonite or soil-cement slurry wall. All of these elements are intended to improve the stability conditions of the slope and achieve a factor of safety (FoS) equal to 1.5 (ACIS, 2010), which is considered an adequate value due to the importance of this infrastructure.

4.1 Drainage system

The drainage system is indispensable within the stabilization process, because the reduction of the water table leads to the decrease of the pore pressure, thus increasing the resistance of the ground to shear stresses. [Collins and Znidarcic (2004)]. Therefore, in search of greater resistance, it is intended to allow runoff water to have a free flow without affecting the stability conditions of the soil mass. Initially the construction of ditches and sub-horizontal drains is proposed. Ditches must be located at the medium-high portion of the slope, to capture part of the runoff water and evacuate it in a controlled manner. Regarding the drains, a length of 30.0 m on the east side of the slope is estimated, so, that the discharge is made in the natural channel of that side since this does not affect the infrastructure of the plant

Finally, for the slurry wall, its position was carefully selected so that the retained water flows towards a region where finally is controlled by the sub-horizontal drainage system. The slurry wall may be alternative substituted by a systematic grouting injections of 10 cm diameter and 20 m length; the drill holes for the injections are arranged geometrically in plain view as a "quincunx" pattern with separation of 1.0 m between drill holes.

4.2 Alternative 1- Anchored pile screen

It consists of the construction of an anchored wall (tangent piles), located in the lower section of the slope, precisely in toe of the mass movement, in order to isolate the discharge channel from the influence of the mass movement and generate a condition of long-term stability.

The piles of the screen have been sectored according to the range of depth and the height of the cantilever. A specific geotechnical and structural analysis for each one of the sectors with respect to the mentioned height was carried out. In addition to the piles, a geometric reconfiguration of the slope (cuts properly located) is considered, which decreases the length of the thrusts on them, in order to obtain a better performance from the structural point of view.

The piles are 33.0 m long (mean value) and 1.8 m in diameter, joined by a head beam. The separation is 3.0 m between axes and the free space between piles is covered by a slab that prevents the passage of material between them. Anchor lines are added; the central piles will have a greater number of lines because they have to withstand greater thrusts. These piles will have four anchor lines with lengths of 27.0 m, 29.0 m, 30.0 m and 32.0 m, and loads in the range of 450 kN to 900 kN. The anchor lines are separated 2.5m vertically.

Finally, when implementing this alternative in the slope, safety factors of 1.5 in the static condition and 1.06 in the pseudo static condition are obtained, thus meeting the standard according Colombian codes.

4.3 Alternative *2*- Geometric modification

This solution is based on the geometric reconfiguration (massive cuts in the slope) alternating slopes and berms to achieve the required stability. In addition, it is necessary to construct a platform of approximately 12.0 m wide in the base of the slope for facilitating the construction of the discharge channel.

For this alternative, it is first necessary to remove the landfill located at the top of the slope. Then, four 15.0 m high banks with variable inclination will be dug. The inclination of the two upper banks will be 2.0H: 1.0V and the last two will be 1.0H: 1.0V. In the middle, there will be 10.0m and 7.0m wide berms

When analyzing the stability of the slope with this new geometric configuration, a safety factor of 1.2 is obtained. This value of safety factor is not sufficient to meet the established standard, therefore, additional reinforcement elements to improve stability are required.

For the complementary supports, active anchors of 60.0 m length were considered, with design load of 600 kN and inclination of 15 ° downwards. Also, sub horizontal drains are added, which allow the water table to be depleted.

Finally, the stability analysis was again calculated and a factor of 1.5 was obtained, which meets established factors according Colombian codes.

Figure 3 shows the different alternatives implemented to stabilize the slope.

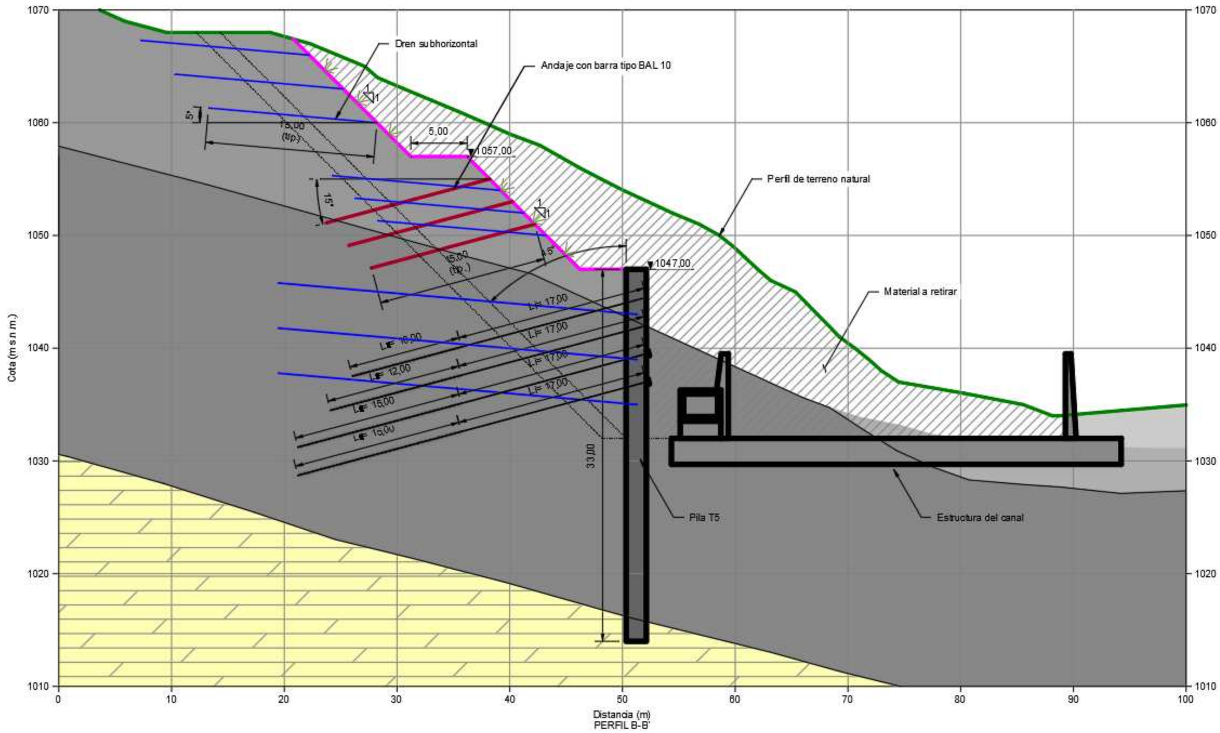

Figure 3. Alternatives implemented to stabilize the slope

5 ALTERNATIVES COMPARISON

To determine which would be the optimal alternative to stabilize the left bank of the slope, a comparison between the alternatives is performed, taken into account the costs, construction time, the management of excavation volumes and environmental requirements.

5.1 Advantages and disadvantages of possible solutions

5.1.1 Anchored pile screens

5.1.1.1 Advantages

i. It is less expensive than making a geometric modification using slopes and berms.
ii. It does not require disposal areas for excavation materials.
iii. It requires a shorter intervention time than geometric modifications
iv. It is easier to carry out the construction process.
v. If the flow that passes through the spillway channel exceeds the design flow, the anchored piles would prevent erosion of the lower section of the slope.

5.1.1.2 Disadvantages

i. The reinforcing elements of the piles and anchors may suffer corrosion [Suarez J., (1998)]
ii. Permanent maintenance May be required (tensioning). [Suarez J., (1998)].

5.1.2 Geometric modification

5.1.2.1 Advantages

i. It allows the reduction of the overturning moments that are produced in the slope.
ii. It allows to build terraces in which structure to control erosion can be established. [Suarez J., (1998)].

5.1.2.2 Disadvantages

i. It is a more expensive alternative than the screens.
ii. It requires a disposal area for excavated materials.
iii. It requires an environmental permit.
iv. It requires more construction time
v. Excavation requires a rigorous process
vi. If the flow through the discharge channel is greater than the design flow, there will be an erosion process in the final part of the slope.

6 CONCLUSIONS AND RECOMMENDATIONS

Currently, the Salvajina Hydroelectric Power Plant is operating without requiring the discharge channel, since the reservoir has never reached the maximum level. If its operation where to be required, the improvement of the stability on the left slope, which has been the object of study of the article, is clearly necessary because the improvement of this conditions increases the safety of the HPP.

Furthermore, an analysis to find the most efficient solution is required, considering the presence of instability problems before the construction of the power plant. This means that the adequate solution should also be effective over a long period of time, since these issues have been present through several years. However, before seeking a specific solution, water management is an important factor because if this is not handled properly, none of the alternatives will be able to fully accomplish the slope stabilization objectives due to the presence of high ground water levels.

However, when selecting a stabilization method, special importance to the geological and geotechnical characterization of the site should be given, because a thorough and detailed knowledge of the terrain conditions allows the determine of weakest points or the areas that face the highest risk, as well as the acknowledgment of land movements or events that have occurred throughout the years, which enables the recognition and prevention of possible future events.

In addition to this, before choosing a method of stabilization, all the constructive and legal limitations that each of the options may have must be considered; For example, the screens in anchored piles and the anchors, present constructive limitations in this area, due to the amount of strata of different materials present on site, which can cause problems when doing the excavations. On the contrary, if the geometric reconfiguration is analyzed there may be legal limitations, due to environmental regulations that makes it increasingly difficult to access the areas of deposition of sterile material.

The modeling, process, done through the limit equilibrium and finite differences methods, can be regarded as an excellent complement to the analyses and the alternative selection process due to the fat that is option could be studied in detail and all possible circumstances could be considered, which allowed opportune modifications or solutions if needed.

Finally, it is necessary to highlight the great importance that these infrastructure projects have within the progress of the country. In addition to contributing to the development of the engineering field in the country, these types of plants generate clean and also the most efficient energy due to the large number of watts they can offer to the population, preventing the country from being obliged to buy energy.

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