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ABSTRACT

An ancient landslide is situated in the vicinity of one of the two reservoirs of a pumped storage power project. Ground movements of the landslide accelerated following the construction of the reservoirs about thirty years ago. Though at a relatively low rate of movement, the active landslide jeopardizes the serviceability of transmission lines and roads traveling through the landslide area. The landslide also poses a potential threat to the adjacent reservoir.

Based on long-term monitoring and thorough engineering investigations, remedial measures were developed and implemented in an effort to stabilize the active landslide. Different facets of the remediation construction were proved to be challenging. While the remedial construction appears to have been effective, continuous monitoring of the landslide is believed to be indispensable in assessing the performance of the remediation. This paper discusses monitoring techniques, historical monitoring data, the mechanism of the landslide and the methodology of the adopted remediation.

INTRODUCTION

Located in the Catskill region of New York State, Bleheim-Gilboa Pump Storage Power Project has a generating capacity of approximately 1,000 MW. The Project was constructed in 1973, and consists of two reservoirs connected by penstocks and a pumping-generating hydro-power plant.

Encompassing an area of approximately 100 acres, the landslide fringes on the western (right) bank of the Lower Reservoir. The landslide existed prior to the construction of the Project; nonetheless, accelerated following the filling of the reservoirs. The movement of the landslide, naturally in the down slope and towards the reservoir direction, not only posed potential threats to the reservoir and dam, but also caused movements of power transmission towers and, in turn, additional tension stresses in the power lines located within and near the landslide area.

The location of the landslide area in relationship to other main project features is illustrated in Figure 1.

Following an extended period of monitoring of the landslide, an engineering investigation was performed to develop the remedial design and subsequent construction. Construction was largely completed in 2001. Monitoring of the landslide has been continuous prior to, during and after the remediation. The monitoring data are used as the primary means to assess the performance of the remediation. This paper, while presenting engineering background of the landslide, focuses on the monitoring landslide behavior prior to and after the remediation construction. Movement of the landslide was noticed after the construction of the pump-storage power project. A systematic monitoring program of the landslide movement has been implemented since 1994. The monitoring program primarily consists of nine inclinometers and four Global Positioning System (GPS) receivers.

ENGINEERING EVALUATION AND REMEDIATION

A comprehensive engineering investigation was carried out in 1997 and 1998 by Paul C. Rizzo Associates, Inc. The engineering investigation mainly involved study of regional geology, field reconnaissance and mapping of the landslide area, subsurface exploration and testing, review of historical monitoring data. The engineering investigation not only fumishes a better understanding of the geologic settings of the landslide, but also produced a more accurate delineation of the extent of the landslide. Results from the engineering investigation were used in the following engineering analyses for remediation design.

The remediation construction started in the summer of 2001 and was largely completed by the end of the same year.

Geotechnical Conditions

The landslide is situated in the Catskill Mountains of the

Appalachian Plateau Physiographic Province. The area is glaciated and can be characterized by rugged topography with steep mountains and narrow valleys. Elevations commonly reach 2,000 feet above mean sea level (ft., MSL) with relief of 1,000 feet or more. Four major intervals of glaciations reportedly occurred during the Pleistocene Epoch, which occurred from 10,000 to two million years ago, often characterized by multiple advances and retreats of ice. The most recent ice sheet advance was the Laurentide, which occurred during the late part of the Wisconsian Stage (Woodfordian Substage) approximately 8,000 to 15,000 years ago. This glacial advancement destroyed most of the evidence left by earlier glaciers.

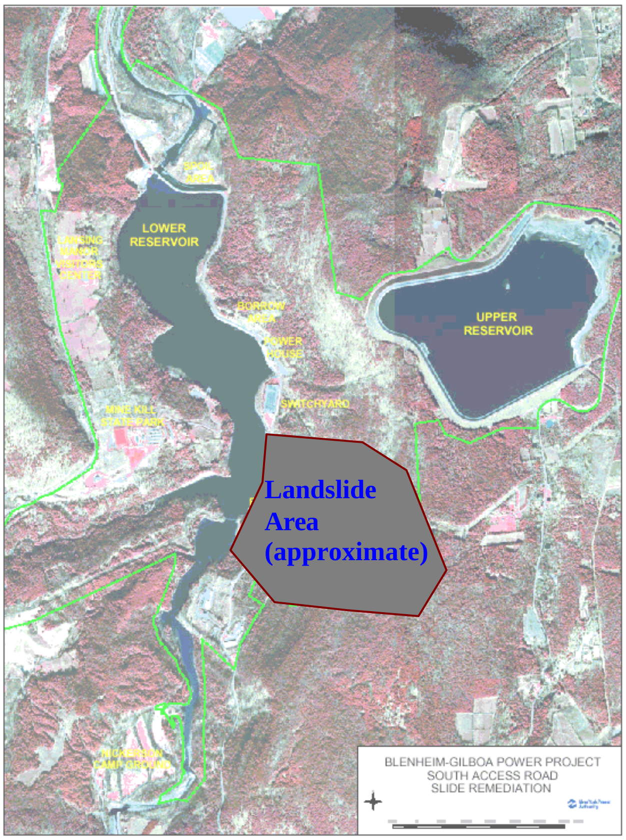

Figure 1. Location of the Landslide

Both the thickness of soil deposits and the depth to bedrock are highly variable at the site. Drilling activities at the site indicate thick sequences of glacial till deposits and thinner interbedded lacustrine (clay) layers which overlie the bedrock. The thin varved clay layers are believed to be the potential failing zones of the landslide. These units are characterized as gray to reddish gray, varved clays with red silt laminations. The clay unit is very thin to absent uphill, but it ranges from 2 to 15 feet thick downslope near the Lower Reservoir.

Table 1 summarizes the strength parameters based on laboratory testing on clay samples extracted from the failing clay layers. The strength parameters presented in Table 1 were obtained from a series of consolidated drained directed shear tests under different confining pressures.

Table 1 Summary of Shear Strength of the Varved Clay

Shear Strength Parameters	Peak	Residual
Cohesion, c' (kPa)	0.7	28.3
angle of internal friction, ϕ'	21.6°	9.3°

It should be noted that the value of residual ϕ' would be approximately 13.5° if no cohesion is assumed.

Bulk analysis of crystalline phases testing by X-ray diffraction (XRD) on two clay samples was also performed. The only types of clay minerals identified from the XRD testing were chlorite and illite. No expandable clay minerals (montmorillonite, bentonite and etc.) was detected in either sample. The absence of expandable clay components indicates that the site clay units are internally stable. It can be further surmised that the observed landslide movement is not likely to have been caused by the expanding and contracting of the clay minerals themselves, but rather as a result of the relatively low shear strength of the clay materials and the driving forces of the landslide.

<u>Engineering Evaluation and Analysis</u>

Following the engineering investigation, different alternatives were considered to mitigate the landslide movement and threat to the integrity of the transmission line located within the landslide area. The feasibilities of several remediation schemes, such as heel excavation, drainage, buttressing, and multiple tied-back walls were studies. After considering factors such as constructability, environmental impacts and cost-effectiveness, the buttressing option was recommended as the remediation design.

The buttressing remediation mainly involved the construction of a rock-filled berm along the toe of the landslide. Another key component of the remediation is the construction of drainage channels to systematically divert surface run-off away and off the landslide area.

To reduce the construction costs, on-site rock quarry was also adopted. Suitable overburden soils excavated from the quarry area were used for improvement of the existing Lower Reservoir Dam.

Key site structures, such as the transformer equipment, the switch yard, the power house and dams were carefully instrumented and monitored during each rock blasting operation to ensure that the construction activities, especially the rock blasting operations would not pose any adverse impact on the structural integrity and normal operations of the power generation facilities.

The remediation construction began in July and was largely completed by the end of 2001. A total of over 200,000 cubic yards of rock material was placed to complete the construction of the toe berm. Figure 2 shows a photo taken in February 2002 of the completed toe berm.

MONITORING OF THE LANDSLIDE

Four inclinometers were installed in the landslide area prior to the remediation construction. Among these four inclinometers, two (IC-1 and IC-2) were installed at locations near the toe of the landslide in 1994, with two more (IC-3 and IC-4) were added at upslope locations of the landslide in 1997. Historical measurements of the inclinometers generally indicated that significantly more landslide movements near the toe, and relatively less movements in the upslope areas of the landslide. The two lower inclinometers had to be replaced at least once due to excessive shearing deformation of the casings.

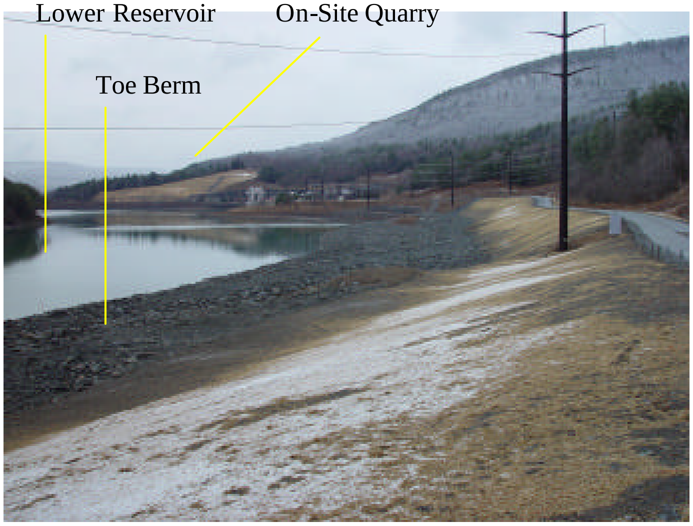

Figure 2. Completed Rock-filled Berm at the Toe of the Landslide

The inclinometer field readings have been taken on a monthly basis. The historical displacements measured at one of the downslope inclinometers (IC-1) are shown in Figure 3. For presentation clarity purpose, Figure 3 shows one set of inclinometer data for each year. A distinct shear zone of about 8 feet think located at a depth of approximately 60 feet below the ground surface can be observed in Figure 3. It can also be noticed that the landslide movement has slowed down since the October 2001 measurement.

More monitoring data measured at IC-1 location are shown in Figure 4 which plots the historical movement measured at about 8 feet below the ground surface and in the general east-west direction.

Figure 4 indicates that the ground movement at IC-1 location averaged at about 3 inches per year during the first year of the measurement, and then decreased to an average of approximately 0.53 inch/year in the following three years of period until the time of the remediation construction. Shortly after the commencement of the toe berm and surface water drainage system construction, movement at IC-1 has virtually been steady as indicated in Figure 4.

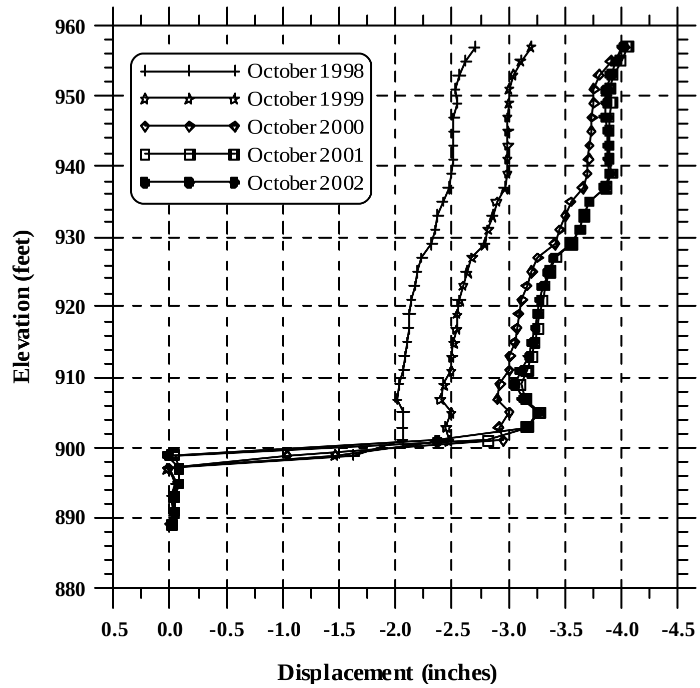

Figure 3. Measured Profile at IC-1

The landslide movement was also previously measured by traditional survey which was performed annually. The land survey was time-consuming and costly. A Global Positioning System (GPS) was installed in December 1999 as part of the monitoring system of the landslide. The GPS mainly consists of four receivers, a base station and a dedicated server computer. Each of the GPS receivers is strategically located in the vicinity of a power transmission tower. Three of GPS receivers (REM-1, REM-2 and REM-4) are situated along the lower part of the landslide, whereas one (REM-3) is near the top of the landslide.

Unlike the inclinometers, GPS measures the movement in three dimensions (longitude, latitude and elevation) at each installed receiver location. When significant movement occurs, the system can notify responsible parties based on measured movements and established threshold values.

The system is capable of acquiring and processing a large amount of data in virtually real-time. The data acquisition frequency of the GPS is adjustable. In this particular application, the data acquisition frequency is set at every 5 seconds. The processed GPS data can be accessed and reviewed from remote locations via network.

GPS data have shown that the predominant movement of the landslide is in the longitude towards the west (downslope) direction.

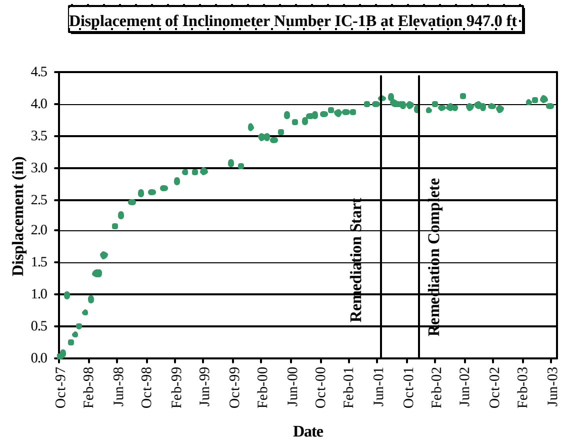

Figure 4. Historical Near-Surface Movement at IC-1

The GPS measured landslide movements in the longitude direction are summarized in Figure 5. GPS measurements are generally consistent with those measured by the inclinometers. Based on our experience at this project, it is believed that the GPS is relatively more accurate than the inclinometers. However, GPS seems to demand more advanced maintenance and trouble shootings.

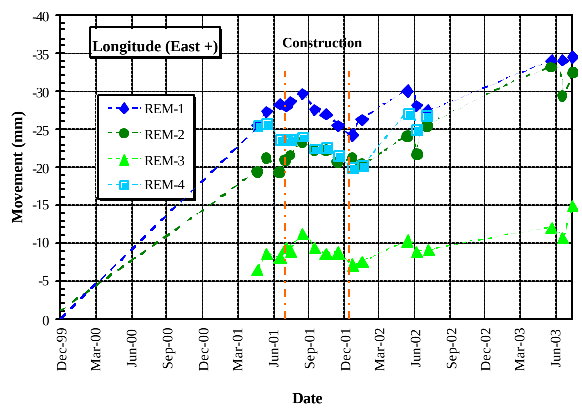

Figure 5. Landslide Movements Measured by GPS

Thus far, even only one and a half years of monitoring data are available since the completion of the remediation construction, it seems that the movement of the landslide has decreased noticeably. The observed stabilization trend of the landslide is believed to attribute to both the toe berm and the surface water diverting system.

However, continuous monitoring is believed to be essential not only for the need to further assess the long term performance of the remediation, but also for the assurance of the wellbeing of the facilities and structures located within and close to the landslide.

SUMMARY

An active landslide was detected following the construction of a hydro-power project. After close monitoring and comprehensive engineering investigation, the remediation was devised and carried out to mitigate the potential hazards that the landslide posed to power transmission lines and other facilities. Although the amount of monitoring data since the completion of the remediation project is fairly limited, the construction seems to have performed according to the intended purpose of reducing or stabilizing the landslide.

It is realized, however, long-term monitoring is essential to evaluate and to confirm the performance of the remediation. The existing monitoring program, mainly consisting of nine inclinometers and a GPS network, also serves as a surveillance system to ensure the normal operation and the safety of the power generation project.

REFERENCES

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