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Impact of operation of hydropower reservoir on slope stability. Comparison between manual and automatic inclinometers.

Impact du fonctionnement du barrage hydroélectrique sur la stabilité des pentes. Comparaison entre inclinomètres manuels et automatiques.

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ABSTRACT: Inclinometers are widely used for measuring horizontal displacements in ground as well as in structural elements. In particular the observation of natural creeping slopes demands inclinometer measurements of high accuracy. It is therefore essential to assess the reliability of inclinometer measurements in a systematic way. This contribution deals with the examination and determination of accuracy and precision concerning inclinometer measurements. This paper presents one case for understanding and interpreting slope inclinometers, manual and automatic. Inclinometer measurements will be discussed based on the actual impact of a hydropower reservoir on an old and still active landslide. The case is an approx 0.5 km^2 large slope in the Albanian mountain range. The slope has a history of slow creeping, requiring re-building of houses every decade. Operation of a newly build hydropower plant requires constant monitoring of the slope deformations to ensure the safety of the habitents.

RÉSUMÉ: Les inclinomètres sont largement utilisés pour mesurer les déplacements horizontaux dans le sol ainsi que dans les éléments structurels. En particulier, l'observation des pentes rampantes naturelles exige des mesures d'inclinomètre de grande précision. Il est donc essentiel d'évaluer la fiabilité des mesures d'inclinomètre de manière systématique. Cette contribution traite de l'examen et de la détermination de l'exactitude et de la précision des mesures d'inclinomètre. Cet article présente un cas de compréhension et d'interprétation des inclinomètres de pente, manuel et automatique. Les mesures d'inclinomètre seront discutées en fonction de l'impact réel d'un réservo hydroélectrique sur une ancienne pente de glissement de terrain active. Il s'agit d'une large pente d'environ 0,5 km2 dans la chaîne de montagnes albanaise. La pente a une longue histoire de lente progression, nécessitant la reconstruction de maisons tous les dix ans. L'exploitation de la nouvelle centrale hydroélectrique nécessite une surveillance constante des déformations de la pente afin de garantir la sécurité des résidents.

Keywords: Landslide, monitoring, slope stability, inclinometers, dam

Banja dam

1 INTRODUCTION

Banja hydropower plant is located in Cërrik Municipality in Elbasan County, 65 kilometres southeast of Albania's capital Tirana. The power plant was officially opened in September 2016 as the first plant to be completed by Devoll Hydropower Sh.A. (DHP), an Albanian-registered company, owned and operated by Statkraft (Norway).
Construction of the Banja Dam was started in the 1980s and abandoned in the early 90s with the dam foundation, Bottom Outlet and Headrace Tunnel partially completed. The construction Works were re-started under the present Concession Agreement by Statkraft in 2013. The plant has three Francis turbines with an installed capacity of 72 MW. A dam height of 80 metres gives a reservoir with a total volume of 391 billion litres of water, covering an area of 14 square kilometres.
The Devoll project in Albania consists of two power plants, Banja and Moglicë, with a total output of 256 MW. Moglicë will open in 2019. In total, the two plants will have an annual production of around 700 GWh, which represents a 17-percent increase in Albania's total energy production.
During the Detail Design phase of the Banja HPP it was detected that there are areas around the reservoir which are actively creeping. In order to monitor these area, as monitoring system was implemented. As a results, there were installed 14 Inclinometers, 17 Piezometers and
48 Surface markers installed at at the Banja Dam. At the other active creeping area of Zgjupë, 10 Inclinometers, 10 Piezometers and 51 Surface markers were installed. This paper will focus on the active area of Zgjupe and the impact on dam operation.

2 GEOLOGICAL SETTING

There are 3 geological units present in the location of this case:

- lower Oligocene flysch deposits-
- Middle Oligocene –

- Quaternary deposits

In the case location of Zgjupe are the following units found:

- Deposits of Lower Oligocene and Middle Oligocene (Pg31-Pg32) -consisting of weak, weathered flysch, sandstone and rarely conglomerates. Generally, they form unstable slopes.
- Quaternary deposits Q4 – represented by alluvial deposits consisting of siltyclay, siltysand, sand and gravel; and delluvial - elluvial deposits consisting of siltyclay and gravel. They are firm and consolidated.slide modes

3 FAILURE MODE

Based on data obtained from field studies and laboratory analyses, the potential slide modes are considered as follows:

a) The presence of a sloping topography that creates the possibility of sliding due to the weight of rocky materials. The materialworks to restore the state of natural equilibrium which (natural equilibrium)is broken down from human activity and atmospheric factors;

b) Formations that are in this sliding area are alterated rocks (change the structure and texture) by climatic and physic-chemical phenomena. The large colluvial material that is saturated with water creates the opportunity of slide to happen;

c) The precipitations and sometimes the dry climate creates the possibility of infiltrated water in contact with rock formations in different directions; creating instability conditions of slope. Erosion from uncontrolled superficial waters during the rainfall, penetrates the rock slits,that removes the filling material, solube the clay material and create loose leaves of the rocks that fall in the direction of the slide of the relief.

d) The presence of groundwater that fills the clay layers between the limestone layers and creates conditions for splitting the rock into separate blocks and removing them in the direction of the slide.

As a consequence of the experienced slope deformations, the following preventive measures are implemented:

a) Continuous weekly monitoring and reading of automated and manual inclinometer, piezometers and surface markers as input to the operation planning

b) A surface water collection system and stabilisation of waters in case of massive precipitation, is suggested.

Figure 1. Location of Inlinometers and Piezometers

4 INCLINOMETER MEASUREMENTS

The inclinometers at Zgjupe continued a trend 2016 with increased deformation level of “slow” to “moderate” in the main area. The trend continued throughout 2018, despite a relatively high and constant reservoir level until end of summer 2018. The deformation in the winter/ spring months are likely associated with the high precipitation in this period. The majority of the remaining instruments elsewhere in the area remained on the previous level of continuous “very slow” to “slow” deformation velocity. The uppermost instrument in the village of Zgjupë Koder was replaced in spring 2018 by an electronic instrument.

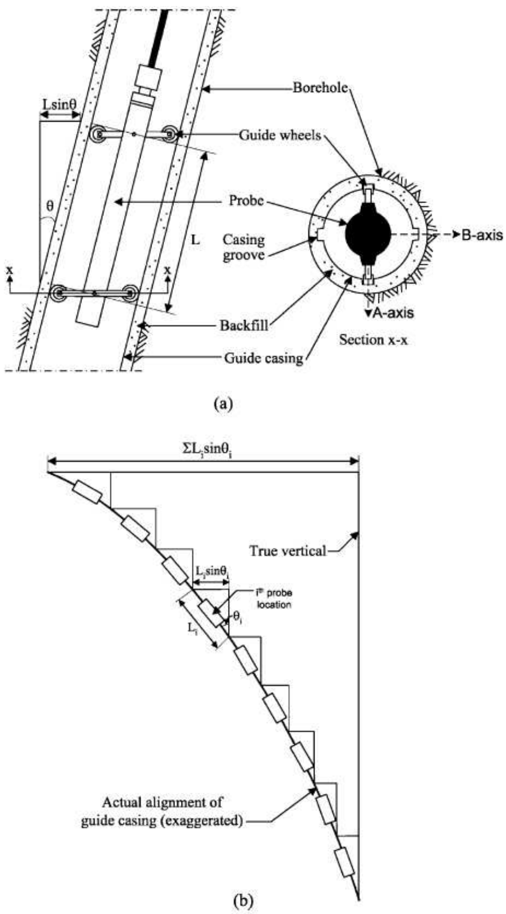

Figure2. a Principles of inclinometer configuration of inclinometer equipments. b Illustration of inclinometer operation (modified from Dunnicliff 1988 and Slope Indicator 2005)

5 INSTALLATION OF INCLINOMETERS

The slope inclinometer installation and interpretation processes involve several important factors so the resulting measurements and difference between the zero and susequent readings are meaningful.When an inclinometer casing is read, two sets of readings are typically taken. The first set is then compared to the second, and the difference between these readings is called the checksum.

The average value of the checksum is good information about how repeatable the two readings were.

This does not, however, compare readings taken on one day to readings taken on another day. To reduce errors in inclinometer measurements, it is recommended that the inclinometer casing be installed as straight and vertical as possible. Errors in inclinometer measurements are proportional to the product of casing inclination and angular changes in sensor alignment. In addition, the bottom of the inclinometer casing shall be firmly fixed to avoid false readings due to casing movement. Thus, the borehole should be advanced to reach stable ground. This assessment should be based on site-specific factors. A depth of about 6 m or more below the elevation of the expected active zone of movement is suggested. It is convenient to advance one borehole to a greater depth than required for inclinometer measurement and to use the bottom length of the casing for checking the instrument.

An important aspect of inclinometer installation is the backfillused between the inclinometer casing and the borehole. The space between the casing and borehole wall needs to be backfilled with grout, sand, or pea gravel to ensure that casing movements reflect soil movement and not simply movement of the casing in the borehole. Among the possible backfill materials, grout is the most desirable backfill because grout provides a rigid connection between the soil and casing so movement of the soil is translated directly to the casing. Thus, it reflects an accurate representation of the soil movement. In addition, if sand or pea gravel is used to fill the annular space, voids can develop where the backfill bridges the annular gap. This gap can allow the casing to deform into the void which will produce errors in the inclinometer measurements and/or false indications of movement,

Mikkelsen (2003) indicates that a random error is typically no more than ±0.16 mm for a single reading interval and accumulates at a rate equal to the square root of the number of reading intervals over the entire casing. On the other hand, the systematic error is about 0.13 mm per reading under controlled laboratory conditions, and it accumulates arithmetically (Slope Indicator 2005). Thus, systematic errors are more important and significant than random errors and should be avoided.

The systematic errors may mask shear movements occurring at slip surfaces and thus should be evaluated and corrected during data processing. Random errors cannot be corrected but are less influential because they tend to remain constant, whereas the systematic errors tend to vary with each survey (Mikkelsen 2003). Thus, the limit for precision for a 30-m measurement (i.e., 60 reading intervals with a 0.5-m probe) is about ±1.24 mm after all of the systematic errors are removed.

The main types of systematic errors are bias-shift error, sensitivity drift, rotation error, and depth positioning error. Systematic errors can be minimized by installation of casings that are vertical and free from excessive curvature and by using mathematical correction procedures.

5.1.1 Bias-shift error

The sensor bias is the reading of the probe when it is vertical.Initially, the sensor bias is set close to zero in the factory, but it may change during field use. If the sensor bias is zero, the readings of A0 and A180 should be numerically identical but opposite in sign. Thus, the magnitude of the bias shift can be evaluated using the checksum, which should be zero if there is no bias shift. However, there is usually a slight bias in the output of the probe. This is referred to as a bias shift or zero shift. This bias-shift error is related to a small change in the bias of the inclinometer probe over time. The bias-shift error is the most common systematic error and can be corrected by the standard two-pass reading of both A0 and A180 directions (Mikkelsen 2003). The bias-shift error can be usually eliminated during data reduction, but sometimes introduces errors if there is a change in the bias between opposite traverse readings, i.e., 180° apart, or if the opposite traverse readings are missed. If the error is systematic, the bias is a constant value that can be added to each reading and appears as a linear component in the inclinometer plot (Slope Indicator 2005). Indicator 2005).

The bias-shift error can be removed by subtracting the algebraic difference between readings of A0 and A180 (i.e., A0 − A180) at each measurement interval. The correction should be made to the measurements in stable ground where no later displacement is expected. Therefore, it is beneficial to have a significant length of the casing in the stable ground, typically, 1.5 to 3.0 m into stable ground (Mikkelsen 2003).

5.1.2 Sensitivity drift

The causes of sensitivity drift are a drift in the operation amplifier in the pre-amplifier of the probe. The sensitivity drift is directly proportional to the magnitude of the readings, and it varies between data sets but is relatively constant for each data set (Mikkelsen 2003). This is the least common error, but it is often the most difficult error to identify. If the error is recognized, it is easy to correct by having the probe factory calibrated and then applying a suitable correction factor (Mikkelsen 2003).

5.1.3 Rotation error

The rotation error occurs when the inclinometer casing deviates significantly from vertical. If the accelerometer sensing axis in the A-axis is rotated slightly towards the B-axis, the A-axis accelerometer will be sensitive to inclination in the B-axis. The B component in the A-axis reading is the A-axis rotation error, as can be seen in Fig. 3. The rotation error angle (Δ) in Fig. 3 can beexpressed as:

$\Delta = \sin^{-1}(r/s)$ (1)

The rotation error can be detected by identifying that the casing is severely out of vertical alignment by the shape of the casing deformation and by observing that the lateral displacement graphs in both directions (A- and B-axes) resemble each other (Cornforth 2005).
Therefore, it is highly recommended to use the same probe during the entire monitoring program.

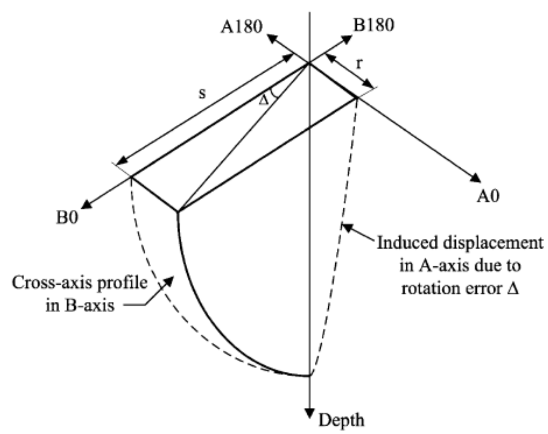

Figure3. Schematic illustration of rotation error as a function of cross-axis inclination (from Mikkelsen 2003)

5.1.4 Depth positioning error

The depth positioning error results from the probe being positioned at different depths than the "zero" readings in the casing. The difference in the vertical position of the probe is usually caused by a change in the cable reference, cable length, and/or compression or settlement of the casing (Mikkelsen 2003; Slope Indicator 2005). Cornforth (2005) concludes that depth positioning errors are not common in most landslide cases, but it is timeconsuming to quantify and correct the depth positioning errors in practice. The top of each casing should be surveyed periodically to determine if a change in elevation has occurred due to slide movement, and the same cable used for the zero readings should be used for subsequent readings.

6 AUTOMATED INCLINOMETERS

SAAF inclinometers are used in Zgjupe . The instruments have been installed in Zgjupe in 2017, when deformations at the most important manual instruments ,hereafter called Z-I-1 and Z-I-2, made it impossible to continue taking manual readings.

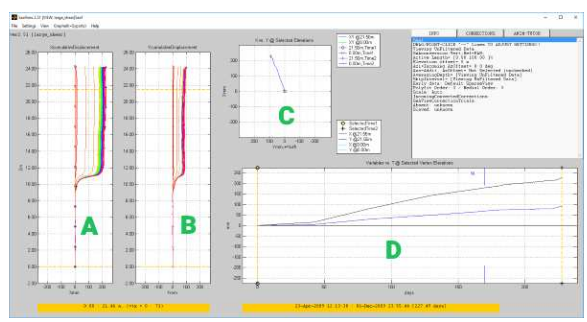

Figure5. Illustration of readings

The results in these instruments can be shown real time, via GSM, or an operator has to collect the data manually.

In general, these instruments are easy accessible and have a longer operational life compared to manual inclinometers as they allow 8-10 times more deformations than manual inclinometers.

7 SITE MONITORING IN ZGJUPE

In Zgjupe there are installed a total of 10 inclinometers, 10 groundwater observation wells and 39 topographic survey points that been regulary measured since April 2016. From 2016 up to now, 4 manual inclinometers have been destroyed due to extensive deformations and are no longer readable. As an example, this paper will focus on one specific inclinometer, called Z-I-1. Z-I-1 is located approx 20 m from the shoreline of the reservoir. Drilling for the initial casing reported extremely poor ground (potential weak rock but with soil characteristics in the upper approx 25 m. Below, a river terrace was reported, suggesting long term sliding in the area. Figure 4 shows an assumed section of the area, including Z-I-1 (fig.4).

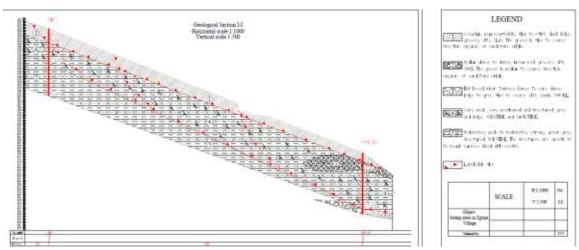

Figure4. Geological Section

The initial manual readings were seized after approx 80 mm of deflection of the pipe. At this point, an SAAF inclinometer was installed in the same casing. A comparison between the initial manual measurements and the SAAF showed a much higher accuracy in the SAAF compared to the manual readings. Where manual readings had a tendency of "meandring" at times, the SAAF showed a clearer trend.

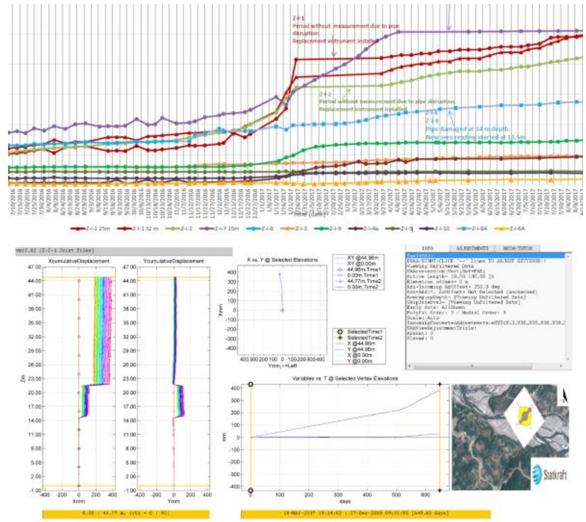

Figure5. Z-I-1 deformations, comparison between manual and automated inclinometers

8 IMPACT OF RESERVOIR LEVEL ON SLOPE STABILITY

As can be seen in figure 5, a significant acceleration in deformations happened in early 2016, leading to deformations in the casing and inability for manual readings. In this period, the reservoiur level was drawn down from the Highest Regulated Water Level (HRWL) continuously to approximately 7 m below.

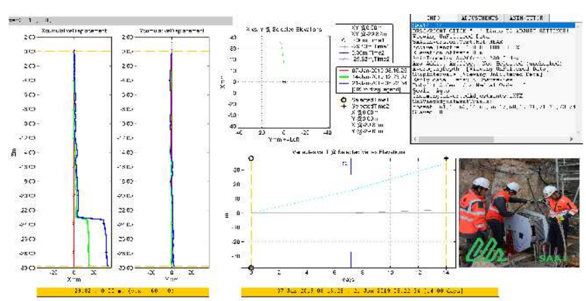

Figure6.Maximum deformations 19mm

After this event it was decided that the lowest operating level of the Banja reservoir should be fixed at 168 masl, and that the reservoir is minimum re-filled to 170 masl and kept there

until all instruments are within their usual deformation rates again.
The reservoir level has therby a huge impact on the slope stability of the area. Nevertheless, it must also be noted that acceleration occurred during a period with high precipitation, despite of a high reservoir level. In such case, it is clear that the over-all stability of the area can only in part be ensured through operational restrictions.

9 CONCLUSIONS

Experience with manual and automated inclinometers have shown that automated inclinometers have a much higher precision and are less affected by bias and human errors. Automated inclinometers have been of great use in operational planning of the Banja HPP.
For this case, the impact of the reservoir water level on the slope stability is significant.
Nevertheless, natural precipitation can override the stabilizing effect of the reservoir.
When filling the lake, more frequent measurements are carried out to control how the reservuar water affects the intensity of sliding action. In Banja Dam a weekly report is been prepared to have all data controled.
Based on the speed of the movement of sliding soil mass, preventive measures shall be taken to protect the Banja dam.

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