Advantages of deformation measurements for a deep excavation of an unstable slope in order to implement a hydropower development

C. Didulescu
Faculty of Geodesy, Department of Surveying and Cadastre, Technical University of Civil Engineering Bucharest, Lacul Tei Blvd., No. 122-124, sector 2, Bucharest, Romania

D. Păunescu, C. Popescu
Faculty of Hydrotechnics, Hydraulic Structures Department, Technical University of Civil Engineering Bucharest, Lacul Tei Blvd., No. 122-124, sector 2, Bucharest, Romania

Abstract. In order to implement the Livezeni Hydro Power Plant on the Jiu River, the construction of the dam required a diversion channel through the left bank. Constructing the diversion channel imposed a deep trench excavation and thus steep slope which often slid in time. In this regard, a bored and anchored column piles support was made, designed for the slope movement control. In this site there is also an important railway. The stringent conditions of displacement control could be ensured by adopting a comprehensive monitoring system using inclinometers. The inclinometer system had to provide both information about the displacement of the column wall and railway track, also revealing any potential crest and slope instability. With the finished columns, the excavations began under their shelter and as the excavation progressed also the two rows of anchorage were rigged-up. Measurements made during the carrying out of the excavation revealed, at a given moment, that the displacements were larger than designed due to the position of initially estimated bedrock. This fact led to the resizing of the anchorage system. The mismatch between the geological configuration, highlighted by the initial studies and the revealed reality on-site was highlighted exclusively by the inclinometer systems, this being one of the major facts that made possible to ensure the stability works. Without this detailed and well integrated monitoring system, the slope stability and traffic safety would have been definitely compromised.

Keywords. Slope displacement, inclinometer, monitoring system

1 Introduction

One of the reasons that changed the slope stability was the excavation at the toe of the slope. This paper presents how the excavation for the diversion channel for Livezeni Hydro Power Plant, at the toe of the slope, created instability conditions and how they were revealed. The chosen solution for the slope instability control was to create a bored and anchored column pile support.

The integrated monitoring system of the slope movement consisted of column inclinometers (noted IC1 to IC5) slope piezometers (noted IP1 to IP9) and topo-geodesic landmarks. The lay-out of the monitoring system complied with the imposed scheme by the initial DE project phase (DE - Details for Execution), with the purpose of an independent monitoring for the pile columns wall, the abutment mass rock, the railway track and adjacent railways works, the slope to the ridge. This system was implemented so that one could diagnose the occurrence of possible instabilities and their causes.

2 Geological conditions highlighted in the works phase. The stability of the column pile wall

In the case of the drilled columns piles the construction works for the left bank slope protection, in the Livezeni dam area, on the Jiu River, TUCEB (Technical University of Civil Engineering Bucharest) participated as expert consultant.

The geological study, originally conducted by a company that activates in the field of geology, was based on Vertical Electrical Sounding (VES) and boreholes that revealed a transversal profile, in the axis of dam, without extending it in the columns wall area. This profile was the basis for TUCEB consultants for the elaboration of the support infrastructure, depicted in the design TP phase (Technical Project) and DE **(**DE - Details for Execution).

The first cues that the profiles were inaccurate emerged in the stage of the boring of the first pile

columns when the contractor complained that the penetration of the bedrock was achieved at higher levels than those highlighted by the geological survey, thus requiring the reduction of the height of the foundation, motivated by extremely high strength of rock.
In these circumstances the consultant expert from TUCEB requested additional on site geological and geotechnical drillings in order to clarify the disaccords noted in the works phase.
The request was rejected by the beneficiary on the grounds of delays already affecting the schedule, and opted for the matching of the design according to the progress of the works. Thus the geological configuration was completed on the ongoing site information related to the progress of the works. This measure imposed very thorough tracking of the evolution of the geological data that emerged from the site and the follow-up of the behavior of the structure and slope through a permanent monitoring system. The decisions about adapting or modifying the constructive solution in order to be operational and that it ensured the safety conditions both for rail traffic in the area and for the personnel involved in the execution had to be taken on the data provided by the ongoing works.
The chosen monitoring system allowed the updating of the geological information and more accurate location of the mobile geological layer, regardless of their origin. The mobile geological layers are responsible for the increase in activity of the thrust-fault, while formations contribute to the stability increase of the pile columns embedding. The position of boundary surface of the mobile geological layers was relative to that depicted in the initial studies, and the revealing of the real lay-out is extremely important. If the boundary would have been lower than the initial estimates, the stress and strain on the active thrust, corroborated with the implementation of a under-dimensioned design would inevitably lead to a considerable increase in the embedding efforts for the pile columns.
This was the reason for the swift intervention of the designer and expert consultant, stated also in the initial project, both in TP and DE phases. As soon as the bed rock would be found 30 cm lower than expected, the consultant had to adapt the design. Unfortunately this provision could not be respected objectively by the contractor due to the presence of breccia boulders, found at higher elevations, which misled into thinking that the actual bed-rock is higher. Moreover, the accredited geologists were not able to note this facts, on the base of the debris examination resulted from drilling the pile columns, in the absence of prior direct investigations. This was the context in which the columns were implemented with an embedded length in the bed rock much lower than initially expected. Once completed, the pile columns, the only means of ensuring the stability of the columns wall remained the anchorage system.
The implementation of the original anchors, at their designed length would create the false impression of intersecting the stabile bed-rock, where as in reality the wall was anchored only in the mobile layers formations.

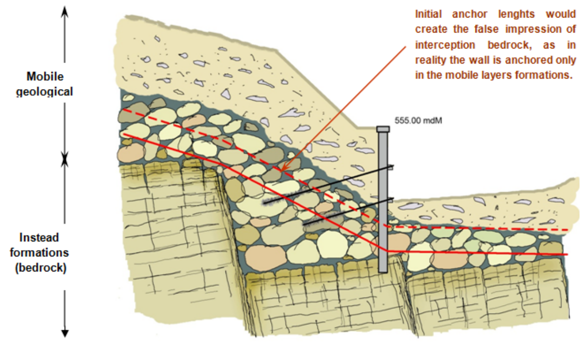

Fig. 1 The anchor length in accordance with the original design did not correspond with the real geological configuration and could not have ensured the stability of the pile columns wall.

3 Inclinometer measurements

In terms of the monitoring system, it has been fully operational since the beginning of the works. The only suspicions were relative to the embedding of the wall in the bedrock due to the drilling difficulties.
The "0" measurement was carried out by a specialized company, but the accuracy and reliability of the information had generated doubts (some readings were reported under the inclinometer sole elevation). For this reason the inclinometer measurements was further carried out by TUCEB. In this case the “0” measurement could not be used as the original reference measurement, so it was redone when the excavations entered the next stage:
- Excavations on the R1 row of anchors was fully implemented until the 550.00 m. ASL;
- Anchors 1- 40 were installed and tensioned to the value of 180 kN as in the DE phase of the design. The remaining anchors on the R1 row (41-68) were carried out at the level of the drilling hole, without attaching anchors;

- From the downstream R2 row excavations were also carried out (546.00 m ASL elevation) up to the last 3 tensioned anchors.

Fig. 2 The state of the works at the moment of taking over the project by TUCEB. Anchor installation

It is important to note that all the results of inclinometer measurements that followed had, as reference, this "zero" measurement, done when already half of the upstream wall was excavated up to the first row of anchors (550.00 m ASL elevation) and on the downstream up to the R2 row of anchors (546.00 m ASL elevation) with the first row already pretensioned. Therefore, all results for the inclinometer measurements are relative to that moment. This was the context the excavations at the diversion channel started, so shortly after the "zero" measurement.

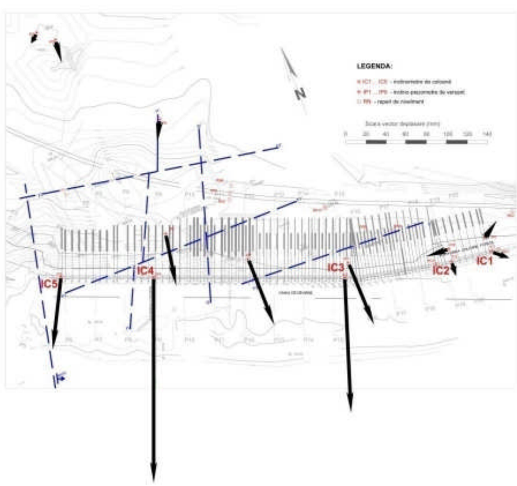

Fig. 3 Position of the pile column inclinometers IC1 - IC5

Figure 3 shows the position of the pile column inclinometers IC1 - IC5 and maximum displacement vectors recorded, in the context of charted recorded displacements throughout the slope.

The highest displacement values were recorded at the IC3 inclinometer with 129 mm and IC4 inclinometer with 171 mm. These inclinometers were oriented perpendicular to the columns wall and their values were rather high, if we take into account that these are relative to a subsequent measurement at the first excavation stage of the downstream panels. These values are generally within the maximum acceptable interval for deformations of the pile columns, as defined by the emergency situations of the initial design, TP and DE phases.

Outlined below are the results of IC4 inclinometer measurements.

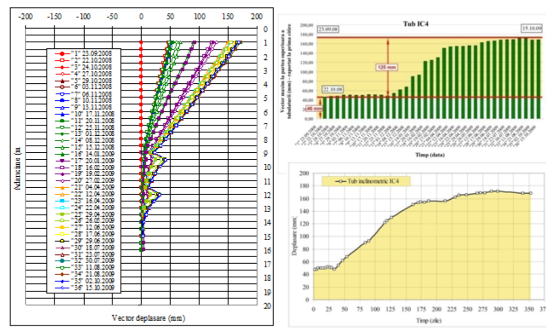

Fig. 4 The measurements results for IC4 pile column inclinometer, depth and displacement vectors. Evolution of the slope displacement vector magnitude recorded during the development works at IC4 inclinometer.

In Figure 5 there are represented, on the same graph, comparatively, the evolutions of displacements measured by IC1 - IC5 column inclinometers, scaled on the time during the works, in order to highlight the comparative evolution of the displacements growth rate and identify the effects of different events.

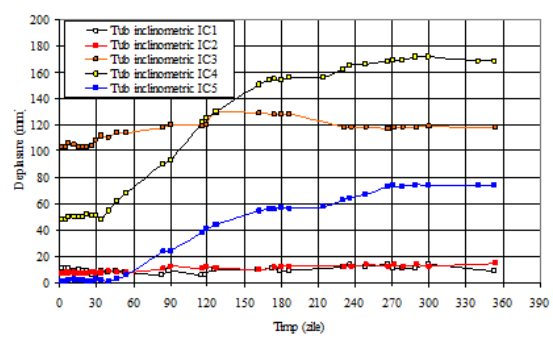

Fig.5 Comparative graph of the evolution for the displacements recorded by IC1 - IC5 pile column inclinometers during the works

In the following we have analyzed and interpreted the piezometer measurements for tubes IP1 - IP9 placed on the columns wall to the ridge, of which:
IP1, IP2, IP7, IP8 and IP9 are inclined piezometers that monitor the behavior of the rock massive between the pile columns wall and railway;
- IP4, IP5 and IP6 are inclined piezometers that monitor the behavior of the slope from the ridge to the railway track.

Fig. 6 The position of inclined piezometers IP1 - IP9 in the work location and the maximum recorded displacement vectors (1 m below ground level) in the context of recorded displacements throughout the slope.

By analyzing the magnitude and orientation of the slope displacement vectors we can make the following observations:
- Displacements size gradually increases from the crest of the slope to the columns wall, correlated with the usual behavior of slopes subjected to deep toe excavations. The maximum displacements recorded throughout the works, corresponding to the depth of 1 m below ground level, gradually ranging between about 6 mm in IP6 and about 67 mm in IP1 and IP7. This distribution of displacements invalidates initial fears related to the triggering of local instabilities, independent from the deep toe excavation, which could affect the railway track.
- Orientation of the displacement vectors deviates from the direction of the excavation, being rotated and relatively perpendicular on the longitudinal fault lines, suggesting an overall displacement for the mobile covering layer formations, controlled by the bedrock line. These formations are not controlled by the largest slope line of the terrain as expected. The exception comes at IP8 and IP9 tubes, located at the downstream end of the wall, where fillings prevails and where the excavation was not completed, at the toe of the wall. All other piezometers have confirmed these allegations.

As the carrying out of the excavation at the diversion channel, from upstream to downstream, monitored by the system (IC3 and IC4), an increase of displacements and fine cracks above and in the key of downstream portal of Aluniş tunnel were noticed, also confirmed by the slope inclinometers. Towards downstream, in the area of the ditch and railway canton, on a sector of a few tens of meters, a crack separation between the canopy beam cover and the massive rock was noticed, confirmed by the reading values of the IC3 inclinometer (about 11 cm), which induced concerns on the maximum cumulative displacements, that should have not exceed 16 cm in emergency situations.
The displacements were also confirmed by the size of the aperture arising from the concrete connection between the gutter and the pile columns wall. This failure was noticed as a small earthquake, as characterized it by the workers from railroad canton, which left the canton building cracked. Therefore, the displacements of the wall were pronounced in the mid downstream wall section, where the trench is closer to the wall and where the excavation at the toe of the wall was deeper. So the effects were less significant in upstream half, where the trench is farthest and the excavation at the toe of the wall is shallower (only for the first row but not anchored).
The very particular conditions of the site geology led to the implementation of compulsory measures in order to reduce, as much as possible, the inherent risk of anchors inefficiency. As the stability of the pile column wall was already jeopardized by the presence of the bedrock at much lower elevations, the wall elements capable moments could have been exceeded. These taken measures, apparently too harsh, were in accordance with the Romanian and European regulations and have been established with the product specifications, submitted by the dealer companies for compliance.
The analysis of the displacements charts, resulted from inclinometer measurements, both for the pile columns and for the slope, emphasized normal displacements. These also provided a very interesting aspect: namely that the break points, where inclinometers suffered deformations, are located much deeper than previously thought, fact

which confirms that the bedrock formations were much deeper than anticipated.

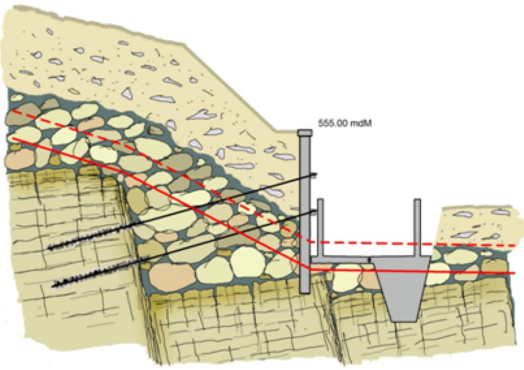

Fig. 7. Pile column wall with the anchors – holding the slope for the diversion channel in the actual on site conditions

4 Technical measures following the analysis of the deformation measurements

After analyzing the deformation measurements it was decided, according to the new image of the site geology, that an increase in length of the anchors should be adopted of 25 m in length and 15 m for the bulbs, maintaining virtually the same free length as in the initial design phase DE, so granting the same stiffness.

Also the geological configuration imposed the implementation of the same type of anchors for the entire columns wall, differently than the original draft, and thus the extra length for the anchors and length for the bulbs of the bottom row. In addition to the strengthening of the railway canton area as compensation of the tension deficit in the R1 row, an additional row (Rs) with 14 anchors was commissioned, pretensioned to the values that, in theory, would have been mobilized in the R1 row in the initial design. For the set-up of this additional row, a new beam anchor was constructed, positioned over the 550.00 m ASL beam and additional fillings had to be done in order to ensure access to this elevation.

Recorrelation of the geology to the new conditions confirmed that many inclinometer tubes were not embedded in the bedrock formation, and that measurements made with these instruments have a relativity factor, meaning that the actual motion observed by the inclinometer has to be added to the displacement of sole drilling.

This uncertainty generated the need to find a new monitoring parameter. The parameter was the tension mobilization of the pretensioned anchors as the height of the excavation was lowered. Thus arose the idea of verifying the residual tensions in the anchors, as a new way to monitor the system status (pile columns wall – slope assembly).

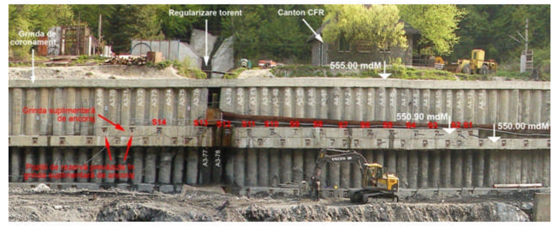

Fig. 8 The general disposition of the additional works, on the trained torrent zone and railway canton. (Additional anchor beam and additional anchors S1 ... S14.)

The verification of the residual tensions in the first 40 anchorages revealed a whole area where the tension in anchors fell on values well below those that would have been achieved after the excavation works.

Checking through residual tensions detachment was successful in the four stages up to the end of the excavations. The results of these measurements are summarized in the chart below resulted from the measurement sheets.

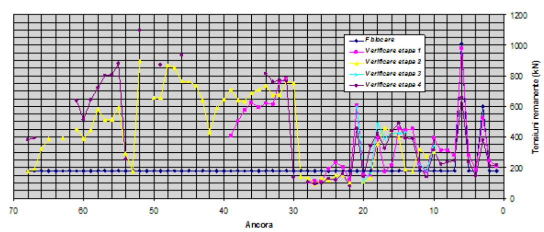

Fig. 9 Verification stages in anchors tensions. R1 row

As shown, in the following stages, tension loss can be observed, but in only in limited areas without major consequences. Graphic representation of the residual tensions in the anchors overlapped on the anchors position on site, reveal an interesting and very precise correlation between the position of the anchors that have lost tension and the position of the faults. Thus the hypothesis of the low stability for the embedded bulbs along the transverse faults.

Figure 10 represents at an undistorted scale of the cross section considered representative through the axis of the dam and downstream, alongside the existing constructive elements or recently completed items (rail tunnel, columns wall, diversion channel).

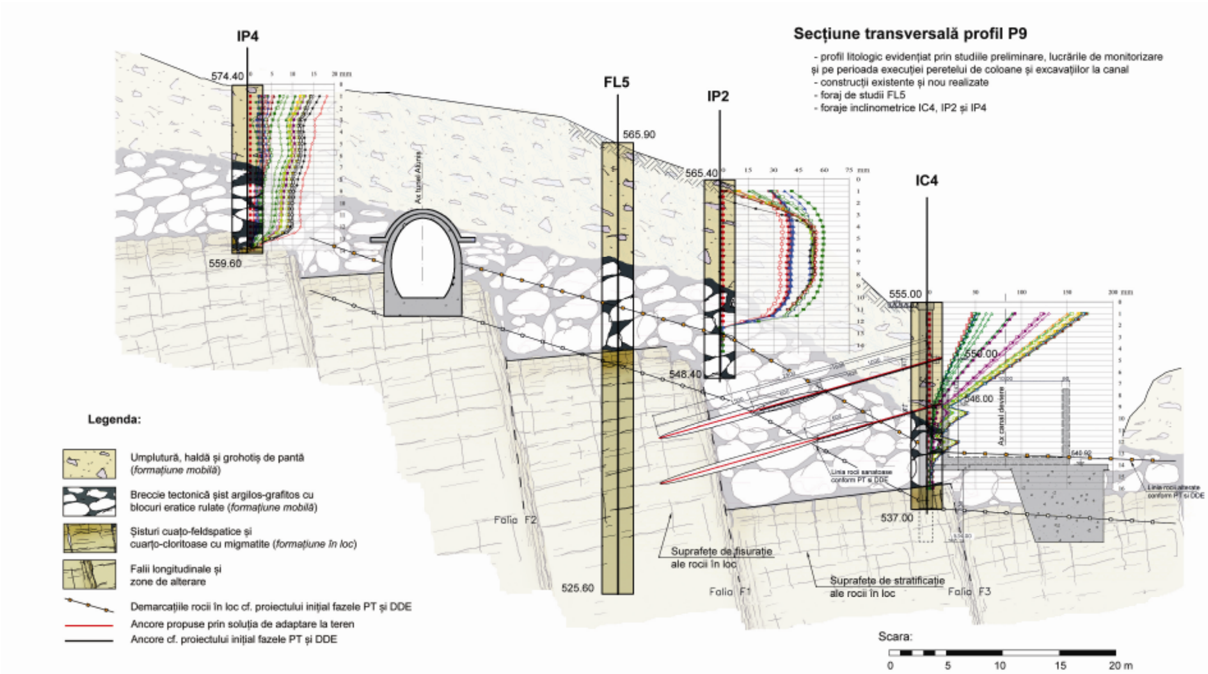

Fig. 10 Representative cross section with synthesis of work studies which imposed a new image of the geological configuration and the need to modify anchoring solution.

There are also highlights on the geological details resulting from the correlation of the information from the boreholes of the old geotechnical study, old inclinometer measurements, execution descriptions of the pile columns and excavations of the diversion channel foundation. All this data led to the conclusion that there is a large discrepancy between the configuration and depth of the bedrock, depicted in the initial project, and the actual on site condition.

Conclusion

The major part of the slope inclinometers were not working, as they should, without the sole embedded in the steady formations. On the other hand, due to the lack of data for the bedrock formation, drilling difficulties were encountered during construction. Consequently, the measurements made on such instruments are compromised, and thus any efforts being spent on their interpretation were pointless. In such cases, the actual, absolute displacements of the massive are certainly higher than those measured, which is why the parallel measurements were implemented in order to monitor the tensions in the anchor assembly.

Despite these serious shortcomings and provisions of relative information, even in quality terms, the monitoring system has proved very useful because it drew attention to the mobility of the formations considered stable and for allowing tracking the evolution of the displacements, even if relative. In this highly unfavorable context, inclinometer measurements led to the decision to implement an additional anchor row and thus increasing the length of anchors, the solution that saved the works stability.

References

*** Columns drilled for protection of left bank slope in dam area on the River Jiu Livezeni - *Contract 53/2005 – Bucharest 2009*

*** Columns drilled for protection of left bank slope in dam area on the river Jiu Livezeni – Summary of geological location and adaptation of anchors to field conditions – *Contract 285/2007 – Bucharest 2009.*

*** Geostudio, User 's Manual, Geoslope International Co. Ltd., Calgary, Alberta, Canada

*** Monitoring report on inclines piezometers and inclinometers at Livezeni slope, Technical University of Civil Engineering Bucharest