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Field testing of weak rock deformation in water tunnels: A practical review of the flatjack test

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ABSTRACT: The flatjack test is normally used to measure the average normal stress at a rock surface and to evaluate the rock mass deformation modulus. The aim of this manuscript is to present a modified variant of the flatjack test for the long-term monitoring of pressure and deformation development in the headrace tunnel of Moglicë hydropower project. The aim is to determine the behavior of the rock mass after water filling of the tunnel and during the first year of operation. The monitoring rig installed will continuously record pressure and deformation development in the rock mass behind the shotcrete liner and data will be stored in the dataloggers submerged in the headrace tunnel. This application is, to the authors' knowledge, one of the first of its kind in hydropower construction. Since data acquisition will not be possible before 2020, this manuscript presents modified test procedure of the flatjacks and rig as a whole. The practical challenges experienced during the instrumentation process of the rig is highlighted.

1 INTRODUCTION

Tunnels in weak rock mass are often subject to stability issues as rock mass from the tunnel periphery deforms and collapses due to de-stressing and due to unfavorable rock mechanical properties. In a strong rock mass, the radial displacements in the tunnel wall are elastic in nature and are so-called time-independent, i.e. the rock loads stabilize soon after excavation. On the contrary, a weak rock mass will fail under medium to high stresses and forms a plastic zone around an opening, and these plastic deformations may continue for longer period (Panthi & Shrestha 2018).

One of the first steps in the assessment of stability of an underground opening is to get an overview of the stress situation and rock material properties. The magnitude and orientation of the stress field at a point within a rock mass can be measured by use of different direct or indirect techniques. However, there is no as such method, which can accurately determine the state of stress at a point of interest (Amadei 1983). A common indirect approach of estimating deformability property of the rock material is the use overburden stress (γH) together with uniaxial compressive strength (σ_c) of an isotropic, homogeneous and linearly elastic medium rock material (Aydan et al 1993). Nevertheless, natural rock mass contain impurities, joints, bedding or foliation planes, folds, shear zones and faults, and the stress situation at a point in the rock mass may vary within short distances (Panthi & Shrestha 2018). In addition, some rock types may easily degrade and change properties when exposed to moisture changes and stress-relief (Erguler & Ulusay 2009), which in turn may interrelate with the site-specific stress situation near the tunnel periphery. Consequently, the behavior of the rock mass surrounding a tunnel periphery or an excavation is in many cases highly anisotropic and non-linear.

From an engineering point of view, disintegration and swelling are among the most serious problems in underground rock excavation and are related to the alteration of previously competent rock mass (Wahlstrøm 1973). In a tunnel in weak rock mass, the time-independent deformation occurs within a distance of two to three tunnel diameter from the tunnel face and time-dependent deformation will continue over a longer period of months or even years (Panthi 2006). In an unlined or sprayed concrete lined water tunnel of hydropower projects, the rock mass will be ex- posed to water causing moisture changes and weakening the rock mass mechanical behavior. This change will have direct influence on the long-term stability of a water tunnel. In this respect, long- term monitoring of the rock mass behavior in the periphery of water tunnel passing through weak rock mass is extremely important. This manuscript discusses the "state-of-art" monitoring approach developed for the monitoring of deformation and pressure development in the headrace tunnel of Moglicë hydropower project. The aim is to use flatjack for the monitoring in-situ swelling pressure and deformation in the headrace tunnel during full operation of the hydropower plant. The manuscript describes installation process of the flatjack, modification and challenges associated to the installation.

2 THE MODIFIED FLATJACK TEST

2.1 *The flatjack test as described by ASTM 2008*

The procedure is described in ASTM (2008) for the Standard Test Method for In Situ Stress and Modulus of Deformation Using Flatjack Method (D4729-08). The test is normally used to measure the average normal stress acting perpendicular to the flatjack plate, but the modulus of deformation and the long-term deformational properties (i.e. creep) may also be evaluated (ASTM 2008). The test principle is easy and unfolds several opportunities in test-configurations and different aims (Mckenney 2018). The initial in-situ stress in the rock mass is relieved by cutting a slot into the rock perpendicular to the surface of the tunnel wall (Fig. 1), and the deformation caused by the stress relief is measured using ASTM Standard D4729.

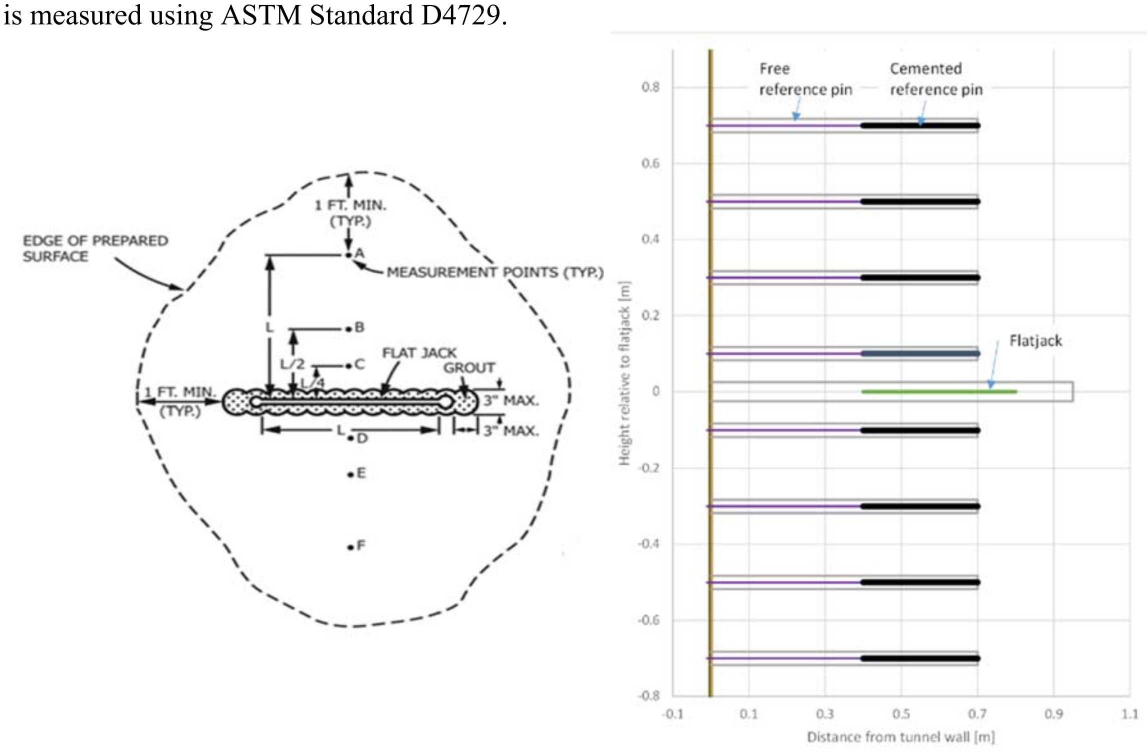

Figure 1. Flatjack array (left) according to ASTM (2008) and modified vertical section of the tunnel wall showing location of flatjack and measurement pins installed in a shotcrete lined tunnel (right).

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The standard requires flatjacks with minimum 600 mm width. The slot is formed by drilling overlapping holes, and it should be maximum 74 mm high and extend maximum 75 mm past the outer edges of the flat-jack. In addition, the slot should be deep enough for the flatjack to be inserted 75 mm beyond the excavation face (i.e. the tunnel wall). Prior to drilling the slot, an array of measurement pins is installed both upwards and downwards from the slot (Fig. 1). The distance between the pins shall be measured immediately before slot cutting and immediately after finishing the slot so that initial relaxation in the rock mass is assessed.

The hydraulic flatjack is centered into the slot, fixed in place with mortar or cement, and pressurized until the pre-slot drilling distance between the measurement pins is again achieved. The standard test is performed by incrementally (0.7 MPa) loading of the flatjack, where the deformation is measured at each increment. To check the time-dependent deformation, the peak pressure should be maintained for at least 15 minutes with deformation readings each 5 minutes, and the procedure should be repeated at least three times using equal pressure increments and decrements. The peak flatjack stress of these repeated cycles should be as high as possible, but it should be adjusted to the rock mass strength, flatjack type and the lock-in pressure. The total reapplied stress is assumed approximately equal to the stress in the rock mass at the test location in the direction perpendicular to the plane of the flatjack. The deformational characteristics of the rock mass may then be evaluated.

2.2 *The modified flatjack test for swelling pressure and deformation*

The site-specific conditions of a tunnel located in weak rock mass will often result in a situation, which departs from the baseline. Hence, the need for modifications on test procedures is usually needed. The flat jack method as described by ASTM (2008) is modified to monitor the swelling pressure development in the rock mass for longer period. Weak rock mass subjected to water saturation and cyclic water pressure change during operation is further weaken and disintegrated over long term. The detection of pressure and volume changes in the rock mass is hence important to understand the swelling potential of the rock mass in-situ. Therefore, the flatjack test method suggested by ASTM (2008) is modified (Fig. 1-right) in such a way that pressure and deformation changes in the rock mass are continuously recorded in the datalogger. The stretch of the headrace tunnel consisting weak and heterogeneous rock mass of flysch formation was selected as locations for the installation of flatjack. In addition, two flatjacks are also installed to monitor the pressure and deformation development in the applied sprayed concrete.

3 BRIEF ON THE CASE PROJECT AND TEST LOCATIONS

3.1 *The case project*

The Moglicë Hydropower Project in Albania is the case project. The project is located in the eastern mountainous part of Albania along the Devoll River, in the southern part of the Alpine fold belt. The project utilizes 300 m water head from a reservoir created by 150 m high asphalt core rockfill dam. The 10.7 km long medium to high-pressure headrace tunnel conveys water from intake to the underground powerhouse cavern close to the Devoll River, with two turbines generating a total of up to 172 MW installed capacity. The rock type at the installation site consists of flysch, an intercalation of thinly foliated clay-, silt-, sand- and limestone layers. The vertical rock cover at the test site is approximately 200 m, with a lateral cover of approximately 300 m.

3.2 *Material description of the Flysch*

Flysch is characterized by rhythmic alteration of sandstone, siltstone, shale and layers of claystone and limestone (Marinos & Hoek 2001). At the project, the rock type is very heterogeneous due to swiftly changing geological environments under fast weathering and erosion processes of a mountain range undergoing rapid uplift. The rock mass is also altered by weathering and chemical alteration where clay minerals are usually present. The Flysch material from the test site is best described as very heterogeneous in terms of color and fabric, with sections of intact core samples alternating with sections of partly or totally disintegrated rock material.

3.3 *Description of the test locations of the flatjack installations*

The tunnel is heavily supported at this location consisting a thick layer of sprayed concrete typically varying between 400 - 600 mm in thickness and closely spaced reinforced ribs (Fig. 2).

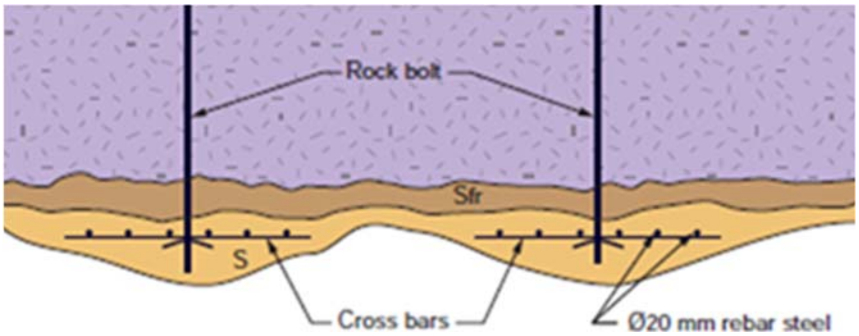

Figure 2. Schematic sketch of Reinforced Rib of Shotcrete.

After tunnel inspection, it was realized that there was insufficient distance between the reinforced ribs to install 600 mm wide flatjacks and the test was modified and scaled down to 400 mm wide flatjacks. In total 8 flatjacks were installed in the headrace tunnel in both sides of the tunnel wall, between chainage Ch.7+489 and Ch. 7+501. The locations of the flatjack installation in the head- race tunnel (HRT) were chosen according to the location of previously tested rock samples from a borehole (BH-1) drilled parallel to the tunnel alignment (Table 1). The assumption is that the in-situ rock material is similar to the rock material from the borehole (BH-1), which is quite logical assumption.

Table 1: Rock sample locations from BH-1 for laboratory tests and flat jack installation locations.

Rock samples from BH-1 at	Swelling pressure (MPa)	Slake Durability Index (SDI4)	Flat Jack installa- tion location	Remarks
Chainage 7+484 (intact rock)	0.24	43.3	Chainage 7+489 (Left wall)	Flat jack on shotcrete, fully grouted pins
Chainage 7+485 (intact rock)	0.20	40.5	Chainage 7+489 (Right wall)	Flat jack in rock, 40 cm outer part of pins free
Chainage 7+485 (weathered rock)	0.16	NA	Chainage 7+492 (Left wall)	Flat jack in rock, 40 cm outer part of pins free
Chainage 7+492 (intact rock)	0.23	48.9	Chainage 7+492 (Right wall)	Flat jack in rock, fully grouted pins free
Chainage 7+495 (intact rock)	0.18	46.2	Chainage 7+497 (Left wall)	Flat jack in rock, 40 cm outer part of pins free
Chainage 7+495 (weathered rock)	0.15	NA	Chainage 7+497 (Rigth wall)	Flat jack on shotcrete, fully grouted pins
Chainage 7+495 (weathered rock)	0.18	NA	Chainage 7+501 (Left wall)	Flat jack in rock, 40 cm outer part of pins free
Chainage 7+495 (intact rock)	0.17	97.6	Chainage 7+501 (Right wall)	Flat jack in rock, 40 cm outer part of pins free

As one can see in Table 1, the swelling pressure and slake durability test carried out in the rock material from BH-1 show a relatively high swelling potential and low durability index when exposed to water. The maximum swelling pressure (SP) of 0.23 MPa was obtained by oedometer swelling tests and the minimum slake durability index after 4 cycles of wetting and drying (SDI4) of almost 40 per- cent was recorded and is considered the most crucial rock material for the headrace tunnel.

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4 THE PROCEDURE OF THE FLATJACK INSTRUMENTATION

4.1 *Preparation of rock surface and cutting of slots*

Installation of flat jacks in an already excavated and supported tunnel is a difficult undertaking for many reasons. Drilling of the slot requires high precision of the core drilling. In the current project, the local specialist geotechnical contractor built a special rig to move the core drill precisely sideways to achieve a horizontal cored slot of parallel overlapping drill holes. In the case of the Moglicë Headrace Tunnel (HRT), the locations in the tunnel had to be prepared to account for the roughness and uneven profile of the shotcrete lining, as well as the tunnels modified horse- shoe shape. Finally, the installation had to consider the installed permanent support of reinforced ribs of sprayed concrete (RRS) which consists of 400 – 600 mm thick sprayed concrete with two layers of reinforcement bars.

Due to the close spacing of the reinforced ribs in the tunnel walls, it was decided to use square flatjacks with dimensions 400 mm x 400 mm. This will, according to the standard require a preparation of an oval area of 1500 mm by 1200 mm in the tunnel wall. In practice, it was found adequate to prepare a rectangular area about 1500 mm x 300 mm and that the reference measurement pins could be installed in an approximately vertical line in the tunnel wall. The locations were manually flattened by chiseling. The slots were cut by overlapping drill holes of diameter 50 mm. For a slot width of 520 mm, a total 12 holes were drilled at approximately 43 mm centers. The depth of the holes was 450 mm for tests in the sprayed concrete lining and 950 mm for tests in the rock mass behind the sprayed concrete lining. The flatjacks installed in the rock mass were at a depth between 400 and 800 mm from tunnel surface.

4.2 *Installation of the measurement pins and initial readings*

Prior to the drilling of the slots, the measurement pins had to be installed. The standard measuring pins consist of stainless steel pins of Ø 12 mm and 200 mm length. To allow for anchoring in the rock mass behind the sprayed concrete liner, the measurement pins had to be extended to ensure that they were anchored in the rock and not the sprayed concrete. Several trials with welding onto different sized reinforcement bars were done, ending up with using 700 mm long Ø 22 mm reinforcement bars (Fig. 1-right) to ensure enough rigidity to get repeatable results. At location Ch. 7+492R, 16 mm Ø bars were used, which proved to be too flexible. The installation at this location was therefore changed to fully grouted measurement pins as described in Section 4.3.

Holes with a diameter of 35 mm were drilled in the prepared locations and the measurement pins were fixed with cement grouting in the rock mass behind the sprayed concrete lining. To avoid grout in the annulus between the measurement pin and the sprayed concrete lining, the outer 400 mm part of the pin was kept free from cement grout by using a plastic pipe, which was removed after the installation.

Table 2: Modified distance of reference points for L with 400 mm (Fig. 1).

Measuring points	Distance from the center line (CL) of flatjack	Position from the CL of flatjack
A	700	above
B	500	above
C	300	above
D	100	above
E	100	below
F	300	below
G	500	below
H	700	below

The positions of the measurement pins were modified to allow measuring with the Huggenberger deformeter with a base length of 200 mm and a resolution of 0.001mm. The measurement pins were set 100 mm either side of the flat-jack (L/4) and then three further points above and below these at

200 mm intervals as indicated in Table 2 (Fig. 1-right). When the grout had hardened, all distances between measurement pins were repeatedly measured with the Huggenberger deformeter by two operators until stable consistent measurements were obtained.

4.3 *Installation of the flat jacks*

The flatjacks were installed parallel to the tunnel radius and perpendicular to the circumferential stress. Due to flexibility issues with measurement pins, two of the flatjacks installed in the sprayed concrete lining, i.e. at headrace tunnel chainage Ch. 7+489L and Ch. 7+497R, respectively. Before installation, flatjacks were de-aired and coupled to dataloggers. The slots for the flatjacks were filled with a rapid hardening mortar and the flatjacks were then pushed into the mortar-filled slot. Mortar was further pushed to ensure the slot was completely filled and tightened (Fig. 3). The pressure measuring transducer were then connected to the flatjacks and set to start recording at an interval of 1 hour on filling and de-airing the flatjacks in order to determine the zero offset. The distances between the measurement pins were measured before and after the flatjacks were installed.

Figure 3. Installation of flatjack in the slot (left) and connection to the pressure measuring transducer (right).

4.4 *Pressurizing the flatjacks and data recording*

The datalogger was set to record pressure at 1 minute intervals for this stage. The flatjacks were pressurized in suitable increments in increasing and decreasing pressure cycles depending on the volume of oil that needed to be pumped and measurements taken to give data that could be used to estimate the deformation modulus of the shotcrete and the rock mass. The volume of oil pumped into the flatjacks was recorded by measuring the oil level in the reservoir on the pump where 1 mm is approximately 0.01 liter. With an area of 0.16 m^2 the 1 liter of oil would give about 6.25 mm displacement if deformation of the flatjack was uniform. The flatjacks were left at a low pressure to observe long term creep behavior and check for any leakage.

All data were downloaded from the pressure transducers connected to the flatjacks. The equipment will be left fully submerged in the tunnel for over a year to register long term pressure and deformation development caused by swelling, disintegration and/or squeezing. The recorded data will again be downloaded during routine inspection after one year of operation.

5 EVALUATION OF THE INSTRUMENTATION PROCESS

The flatjack at Ch. 7+489L was installed in the sprayed concrete, but about 10 mm of the flatjack was exposed in the tunnel wall. The flatjack burst at the exposed seam at a pressure of 15 MPa. Deformation readings were made at approximate pressure of 0 MPa, 5 MPa, 10 MPa and again at 0 MPa pressure in the flatjack. The displacement measurements show an approximately elastic response. Total displacement across the flatjack was measured about 0.7 mm across 200 mm measurement pins at 10 MPa pressure. The displacement of the flatjack according to the amount of oil pumped at 10 MPa pressure should have been about 0.9 mm. It was however, noted at bursting that the flatjack swelled in the exposed part (outer part) by approximately 10 mm indicating that the flatjacks can deform very close to the welded seams.

The flatjack at Ch. 7+489R was installed in the rock mass as the thickness of sprayed concrete was less than 400 mm. Deformation readings were made at 0 MPa, 5 MPa, 10 MPa pressure and again at 0 MPa pressure and re-pressurized to 5 MPa pressure as lock-in pressure for long-term monitoring. The irregular pattern of displacement readings suggest that the measurement pins are in contact with the sprayed concrete in the free section of the hole. The displacement of the flat- jack according to the amount of oil pumped at 15 MPa pressure should have been about 1 mm.

The flatjack at Ch. 7+492L was installed in the rock mass. It was found that the outer part of the flatjack lies in the sprayed concrete since the sprayed concrete thickness here is greater than 400 mm. Deformation readings were made at approximately 0 MPa, 1 MPa, 2 MPa, 3 MPa and 4.6 MPa pressure from where a sudden pressure drop to 0.6 MPa was observed. The pressure in the flatjack was left at this 0.6 MPa for long term monitoring. The irregular pattern of displacement readings confirms that the measurement pins were in contact with sprayed concrete in the free section of the hole. The displacement of the flatjack according to the amount of oil pumped at 4.6 MPa should have been about 6 mm.

The flatjack at Ch. 7+492R was installed in the rock mass as the thickness of sprayed concrete is less than 400 mm. The pressure in the flatjack was increased to 3 MPa after which there was a sudden drop in pressure to 1 MPa. Deformation readings were made at 0 MPa and pressure was again increased to 1 MPa and left at this stage for long term monitoring. The displacement of the flatjack according to the amount of oil pumped at 1 MPa pressure should have been about 9 mm.

The flatjack at Ch. 7+497L was installed in the rock mass. The outer part of the flatjack lies on the sprayed concrete since the sprayed concrete thickness here is greater than 400 mm. Deformation readings were made at approximately 0 MPa, 1 MPa, 2 MPa and 3 MPa pressure in the flatjack. Pressure was then reduced to first 1 MPa and then to 0 MPa. The pressure was again increased to 1 MPa and left at this stage for long term monitoring. The displacement of the flatjack according to the amount of oil pumped at 3 MPa should have been about 2.5 mm.

The flatjack at Ch. 7+497R was installed in the sprayed concrete. Deformation readings were made at approximately 0 MPa, 5 MPa, 10 MPa, 15 MPa and 16.5 MPa pressure at which point pressure started flattening indicating damage in the sprayed concrete. Further pumping was stopped and the pressure was released step by step so that readings at 10 MPa and 0 MPa were registered. The pressure was once again increased to 5 MPa and left at this stage for long term monitoring. The displacement of the flatjack according to the amount of oil pumped at 15 MPa should have been about 0.8 mm.

The flatjack at Ch. 7+501L was installed in the rock mass. The outer part of the flatjack lies in the sprayed concrete since the sprayed concrete thickness here is greater than 400 mm. Deformation readings were made at approximately 0 MPa, 5 MPa, 10 MPa, and 15 MPa pressure and then pressure was reduced with readings at 5 MPa and at 0 MPa. The pressure was once again increased to 5 MPa and left at this stage for long-term monitoring. The irregular pattern of dis- placement readings confirms that the measurement pins were in contact with sprayed concrete in the free section of the hole. The displacement of the flatjack according to the amount of oil pumped at 15 MPa should have been about 0.6 mm.

The flatjack at Ch. 7+501R was installed in the rock mass as the thickness of the sprayed concrete here is approximately 400 mm. Deformation readings were made at approximately 0 MPa, 5 MPa, and 10 MPa pressure and then pressure was reduced to 0 MPa. The pressure was once again increased to 5 MPa and left at this stage for long-term monitoring. The irregular pattern of displacement readings suggests that the reference pins are in contact with the sprayed concrete in the free section of the hole. The displacement of the flatjack according to the amount of oil pumped at 10 MPa pressure should have been about 1.4 mm.

6 DISCUSSIONS AND CONCLUSIONS

The displacement measurements in some locations suggest that the measurement pins are in contact with the wall of sprayed concrete in the free section of the holes drilled for the installation of pins, which may not give true impression of the displacement in the rock mass behind the sprayed concrete. It looks like, there has been rotation or deflection of the measurement pins due to differential displacement in the rock mass. In addition, the deflection may have magnified by the extension of free section of the measurement pins from rock wall through the sprayed concrete. The effort made to set the measurement pins exactly 200 mm apart during installation may have contributed the measurement pins to encounter the sprayed concrete wall of the 35 mm hole. The lessons learned during installation process were useful and should be avoided in the future.

The deflected measurement pins, which came in contact with shotcrete wall, may cause difficulty in relating displacements measured between the pins to the displacement in the rock mass over the long period. Moreover, in some installed locations, the outer part of the flatjacks are laying on the sprayed concrete. Both these conditions should be kept in mind while analyzing the deformation results achieved after measuring the pins and analyzing the pressure development registered in the flatjack for over a year.

The most important observation during the installation process was that the weak rock mass deform at relatively low level of pressure increase suggesting that these rock mass are incapable to hold stresses exceeding certain limit. Flatjack installation in a modified way as have been made at the headrace tunnel of Moglicë hydropower project will give important information in the development of pressure and deformation over the monitoring period of a year when the power plant will be in full operation. The authors are hopeful that the installed instrumentation will function for this period and will be of great value for the power plant operator and scientific community.

The authors recommend that the installation of flatjacks is planned and installed during excavation of the tunnel itself so that interference by the applied support measures is minimized. It is however, emphasized here that the pressure development in the rock mass will be recorded continuously at this project over the long period, which is the main aim of this "state-of-art" monitoring installation.

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