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Continuous Strain Monitoring in the Rock Foundation of a Large Gravity Dam

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Summary

The occurrence of tension fractures in the granitic bedrock at the upstream toe of a dam and unexpected water percolations downstream in the rock foundation gave rise to an extensive investigation program. For the continuous monitoring of strain along different boreholes in the rock the Sliding Micrometer ISETH was applied. This is a portable high precision instrument to measure the distribution of strain along a borehole with the base length of 1.0 m. The accuracy of the setting in the consecutive points is about ±0.003 mm. This makes the device suitable for detecting extremely small deformations which are likely to be encountered in hard rock masses. From the strain distribution along several boreholes with a total length of approx. 400 m a clear picture could be obtained with respect to the location of particular joints which opened as a result of the reservoir filling. The detailed knowledge of the foundation behaviour allowed the necessary remedial measures to be taken against unpermitted water percolations under the dam body.

1. Introduction

The Albigna concrete gravity dam is situated in the south east part of the Swiss Alps at an elevation of 2000 m above sea level in the valley of Albigna, which leads up to the glacier of the same name. The storage capacity of the reservoir is 67 million cubic metres and the total waterhead to the machine house located 6.5 km to the north is 741 m. The dam has a crest length of 760 m and consists of blocks of 20 m breadth. The largest block in the middle of the valley is 115 m high (Fig. 1). Between the blocks there are joint spaces of 5 m in width intended to reduce uplift at the dam base. One can therefore speak of a hollow-joint gravity dam. A special feature of the Albigna hydroelectric scheme is the pronounced rock ridge on which the dam is founded. This formation itself acts as a natural barrier (Fig. 2). In the direction of the glacier there is a natural trough filled with

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about 120 m of alluvion, the rock formation closing it in. In the opposite direction the rock falls away very steeply towards the main valley (Fig. 3). The rock foundation consists of a sound coarse grained granite of high strength and exhibits three regular sets of joints (1, 2 and 3 in Fig. 4). The subhorizontal joints are less pronounced. The distance between the joints varies between 1 and 10 m. The material filling is crystalline which leads

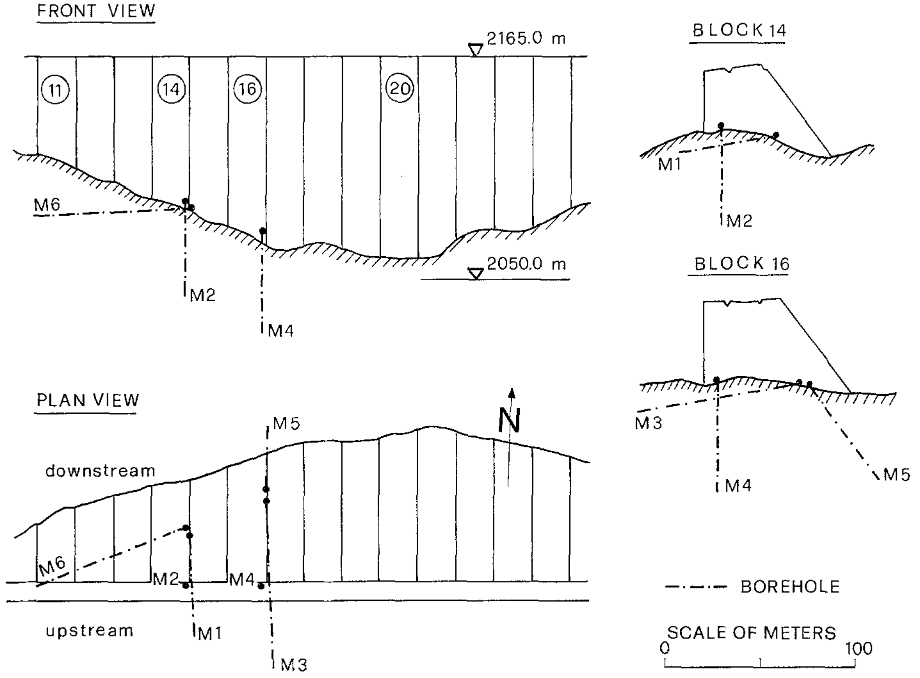

Fig. 1. Albigna Dam. The centre part indicating the location of the boreholes for strain monitoring

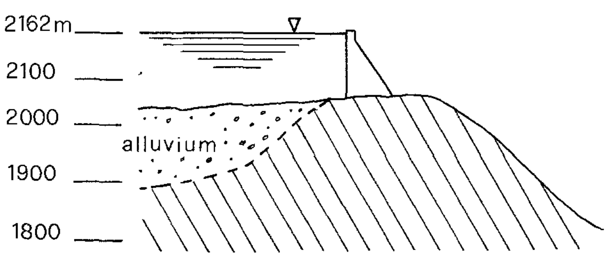

Fig. 2. Section through block 20 showing the marked rock ridge upon which the dam rests

to "healed joints" having a high filling strength. This is of extremely great importance with regard to the deformation and strength properties as well as to the permeability of the rock mass.

In the planning and design stage and also during construction in the period 1956—1959 the foundation rock was considered to be very favourable. Neither the permeability nor the strength of the rock mass were regarded as being problematic for the selected dam type. However, already during the first reservoir filling in the summer of 1960 an unexpected occurrence took place. After the dam had been subjected to the maximum water level for a period of 6 weeks drill holes were made in the course of additional grouting work, also in the vicinity of the foundation of block 11 (Fig. 1). One of these drillholes encountered a small joint, which was under high water pressure. In the process of drilling through the joint the water pressure was suddenly released, leading to a change in the support conditions for block 11, so that within a few hours a fine crack of about 0.1 mm aperture developed in the mass concrete. It extended from the base up to a height of 25 m and it could be clearly observed in the lower control galleries as well as in the hollow-joint of the block 11. It was noticeable that the crack path continued in a filled rock joint belonging to system 3 (Fig. 4). As a result of this crack a relatively small portion of the block which amounted to 900 m^3, i. e. 2.5% of the total volume, was separated. Both for the stability and the state of stress in the block this portion was of almost no significance. The amount of water seeping into the hollow-joint of block 11 was approx. 2 l/sec. By means of grouting and upstream

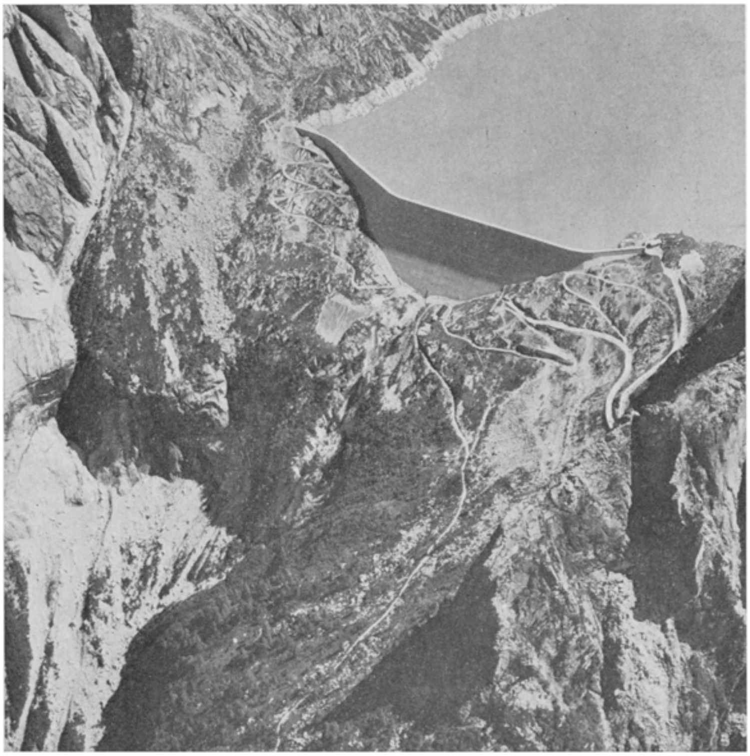

Fig. 3. Albigna Dam. Ariel view looking from the south (Courtesy of Wild Heerbrugg)

sealing of the crack this water flow could be temporally stopped. The loss of water was, however, further observed. Besides this undesirable occurrence the subsequent results of inverted pendulum and survey monitoring in the period 1960—1976 have given no rise to any concern. However, an increase of the crest deflection from 43 mm to 53 mm has been observed in the central section of the dam. In addition, from the distribution of the horizontal displacements along the crest it was readily recognizable that block 11 formed a transition between the central dam portion with greater movements and the left wing which exhibited relatively small deformations. The difference between the permanent displacement in the neighbouring blocks 11 and 12 was 8 mm in 1976. The control measurements with deep seated invert pendulums also clearly showed that the natural rock ridge forming the dam foundation was undergoing deep-reaching elastic and plastic deformations. The tilting movement of the concrete body extended into the rock barrier. (Swiss National Committee on Large Dams, 1982). With the discovery of springs on the left bank of the valley in 1977, to the north of block 11, a change of opinion regarding the dam's behaviour was brought about. Thus this fact together with the recent rise in the amount of water flow into the hollow-joint of block 11, have as a precaution led to a foregoing full reservoir filling. It was also necessary by means of an extensive programme of investigation to obtain a clear picture of what is going on in the rock foundation in order to develop the correct strategy for remedial measures. Their objectives were to stop the underseepage and the tendency to increased deformations.

2. Investigation of the Causes of the Underseepage

In the investigations the starting point was the assumption that there must be a connection between the unexpected increase in deformations and the recent increase in water loss. To clarify these questions the following steps were undertaken:

— Careful visual inspection of the concrete structure to reveal possible cracks, especially at the upstream toe of the dam.
— Drilling boreholes to detect open joints in the rock.
— Installation of borehole extensometers to monitor local deformations in the rock mass.
— Observation of water losses in the hollow-joints in each block as well as the quantity of flowing out at the downstream springs.
— Determination of the path of percolation by colouring the water.
— Theoretical studies with the finite element method.

The 5 m wide hollow-joints between the individual blocks considerably simplified the carrying out of these investigations, since they provided immediate access to the inside of the dam and the foundation area. One of the most important results of the investigation was the detection of an open joint in the rock running along the upstream side of the base of the dam.

The joint extended over a length of 300 m and its aperture was found locally to be up to 8 mm for the empty reservoir condition.

Systematic exploratory boreholes and the displacement measurements revealed that the crack penetrated at least 30 m into the rock formation and as a result of full reservoir filling it opened up to a width of 16 mm at the rock surface. This open joint belonged to the principal set 3 already mentioned (Fig. 4). The investigation of the flow path in the rock mass showed that the springs on the left downstream valley flank were fed not only from the region of block 11 (the shortest path) but also from the more easterly situated block 15.

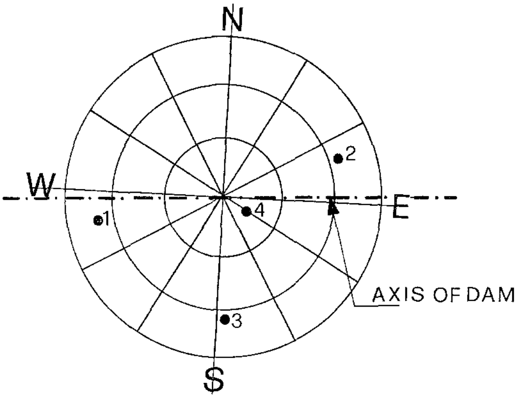

Fig. 4. Main orientation of the four principal sets of discontinuities (lower reference hemisphere)

The great extent of the above mentioned open joint, both lengthwise and in depth, as well as the large volume of rock subjected to seepage clearly showed that the whole middle section of the dam (Fig. 1) had to be included in the subsequent investigations. Special attention had to be paid to block 11, which had given difficulty from the first filling of the reservoir. Measured water loss into the block's hollow-joint, showed a drastic rise in 1977 (Fig. 5). There were also other indications that the grout curtain was fissured in part during reservoir filling in 1977. Thus the water found free access deep into the bedrock under the dam and caused a high hydrostatic pressure in the open rock joints corresponding to the level of water in the resevoir. In the light of this knowledge the stability of large scale rock wedges were reexamined. From the combination of joints in the system shown in Fig. 4 it was possible to identify rock wedges which from a purely geometrical point of view could form a sliding body. There was no acute danger of sliding, but rather an undesirable trend in the structural behaviour of the dam which, when progressing in an uncontrolled manner could at least theoretically lead to detrimental conditions. The actual condition of the dam could not be described as critical in any phase of the investigations during this period. The aim was to bring to a standstill a detrimental process, which had been fully recognized at a very early stage. Measures had to be taken to prevent the development of new joint openings and the further propagation of the existing cracks. Of great importance was the prevention of water percolation into the rock foundation below the dam. However, although the aim was clearly defined, uncertainties existed concerning the following important points:

- Were there other open joints parallel to the longitudinal crack mentioned above, which would terminate perhaps under the alluvium deposit in the reservoir basin?
- What was their extent along the dam axis and in depth?
- Were there further open fissures with large persistence in the rock belonging to one of the principal joint sets 1, 2 and 4 (Fig. 4)?

The last question was of special interest for wedge stability investigations. In this context it should be remembered that the joints were filled with solid crystalline material, which can, however, exhibit only a low tensile strength.

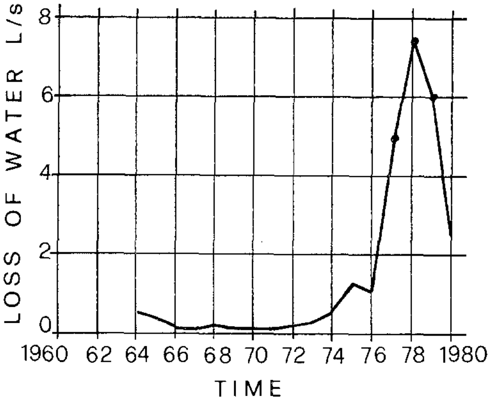

Fig. 5. Seepage into the hollow-joint of the block 11, measured at full reservoir

Answers to the questions formulated above were sought with the aid of systematic high precision rock deformation measurements. For this purpose the concept of "linewise observation" was employed (Kovári and Amstad, 1981) and for the first time the recently developed borehole probe "Sliding Micrometer — ISETH" was used in dam engineering on a large scale. By "linewise observation" the measurement of the distribution of a quantity along a line is understood. Thus with this instrument the variation of axial strain along boreholes can completely be determined with a high degree of precision. In this way the opening or closure of significant discontinuities, which an instrumented borehole intersect, can be observed. Since the field accuracy of the measurements, carried out on a base length of 1 m, is in the range of microns, even very small relative displacements can reliably be observed. These possibilities of measurements were all the more important in the case of the Albigna Dam as only very small deformations would normally be expected in an intact granitic rock. Thus the presence of active discontinuities, which would locally cause larger deformations, could be detected and located. Before discussing the results of the measurement campaign, the measuring technique of the Sliding Micrometer is briefly explained.

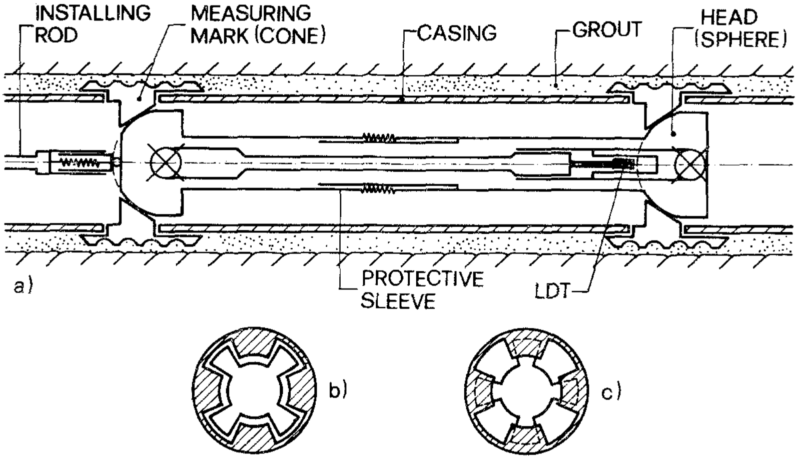

Fig. 6. Sliding Micrometer — ISETH:
a) schematic view, b) sliding position, c) measuring position

3. Measuring Technique with the "Sliding Micrometer — ISETH"

In order to obtain the complete distribution of strain along a straight line, first a hard PVC tube ($\varnothing = 60$ mm) containing ring-shaped measuring marks at regular intervals of 1.00 m is grouted into the borehole. These measuring marks, made of steel, serve on the one hand as coupling elements between two adjacent units of PVC tubes and on the other hand as a housing for stop fittings (Fig. 6). The latter have the function of holding the two heads of the portable device in position during the short time of a reading. The tube segments are screwed into the ring marks and the stop fittings are fixed in by bolting. All connections are such that the whole assembly is sufficiently robust for lowering into a deep borehole of any direction. On the other hand they are soft enough to avoid any "pile effect" along the measuring line. If the measuring marks displace relative to each other due to the deformation of the surrounding rock, then the change in distance, i. e. the strain with the base length of 1.00 m, can be recorded as the difference between two readings. A set of measurements involves the following: beginning at the mouth of the tube the probe is fixed between two measuring marks and a reading is taken. The probe is then traversed in a stepwise manner carrying out readings at each position. After reaching the end of the tube a repetition of the readings is made on retraction of the probe. The two sets of readings permit a valuable check of the actual field accuracy attained.

The main problem in the development of the Sliding Micrometer was to find a mechanically sound yet simple solution with regard to the placement of the instrument heads in the measuring marks. These requirements could be satisfied by means of a special design of the measuring marks and the instrument heads (Kovári et al., 1979). If the measuring marks are in the form of a circular cone and the stops on the heads are spherical-shaped, the position of the centre of the sphere, with respect to the cone, is correctly defined. The accuracy of a setting expressed in terms of strain is within a few microstrains. The measuring marks and the stops on the heads are, of course, only parts of a cone and a sphere respectively, so that the instrument, after a rotation of 45^0, can be passed through the marks and moved along the borehole to any desired position (Fig. 6, b and c).

The construction of the probe is shown schematically in Fig. 6. The two measuring heads are connected by an external spring-loaded protective tube which is stiff against torsion. The inside consists of an invar steel tube, which transfers the relative movement of the heads to a linear displacement transducer (LVDT). The joint connection of the installing rod is seen attached to the left head. The electric cable transmitting the measured values is also brought out there. Since the distance between the measuring heads is smaller than that of the measuring marks, as the probe is set in the measuring position first of all the front head contacts a measuring mark and after stretching the spring on the protective tube the rear head is pulled into the other measuring mark. It is thus ensured that when pulling on the rod both heads are pressed against the measuring marks.

Special features of the Sliding Micrometer:

The instrument is watertight up to 15 bar pressure. Temperature effects are largely eliminated by means of a self-compensating construction. However, to distinguish temperature induced strains in concrete, rock or soil from those due to stresses or creep the instrument is fitted out with a temperature sensor. To control the correct functioning of the probe and the zero-point stability of the inductance transducer a portable calibration frame made out of invar steel is used (Fig. 7). In the calibration frame there are two measuring marks, in which the probe is braced before and after every series of readings. It is worth mentioning, that the alternating operation of setting the probe and sliding it along the length of the casing is made extremely easy by means of an orientation blade in front of the instrument. The forwards and backwards measurements along a 40 m stretch with 40 measuring points only requires about half an hour.

4. Measurement Results

Strain monitoring in the foundation rock was performed along the six boreholes shown in Fig. 1. The length of these boreholes varied between 50 and 85 m having a total length of about 400 m. They were located in the critical area of the dam between the blocks 11 and 16. The orientation of the boreholes is such that they incline steeply to the principal sets of discontinuities. These measurements were expected to furnish detailed information on the frequency and locality of active joints intersecting the measuring lines. By active joints are meant such discontinuities which open or close due to the fluctuation of the water level in the reservoir. It was suggested that such local joint deformations of practical significance would be manifested as singularities in the measured strain distribution curves. Indeed along all six measuring lines such peak values occurred occasionally which doubtlessly point to the presence of active joints. In Figs. 8 to 11 they are marked by a star and provided with a figure indicating the amount of the observed deformation. Before going into details of the interpretation of measurement results, it should be emphasized that the most important finding of the measuring compaign was the detection of the peaks in the strain distribution. Very soon it became clear that only a few active joints requiring special attention were present in the foundation rock of the Albigna dam. Thus, the rock mass below behaves mainly as a homogeneous monolithic body. The active joints designated by A and B in Figs. 8 to 10 belong to the principal joint set 3 in Fig. 4. The joint A intersects both the subhorizontal measuring lines (M1 and M3) and the vertical ones (M2 and M4). In the area of block 14 the borehole M2 is obviously too short to be intersected by the active joint B. The joint A is identical with the longitudinal crack discovered at an early stage of the investigations and mentioned in

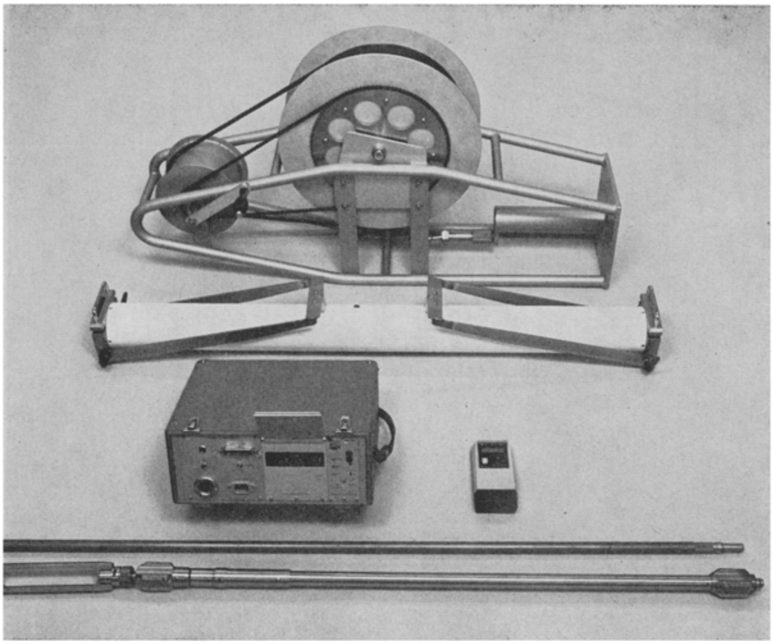

Fig. 7. Sliding Micrometer — ISETH equipment with probe, installing rod, read-out unit, calibration frame and cable drum

section 2 of this report. The Sliding Micrometer measurements just confirmed its existence at depth and gave indication as to the amount of its opening and closing due to the fluctuations of the reservoir filling. The active joint B has been detected by means of the strain measurements. After the removal

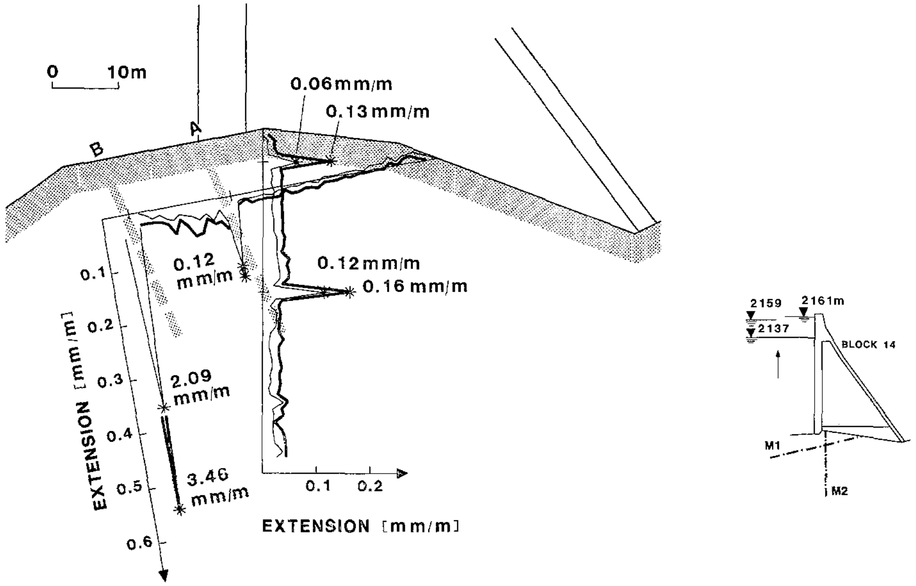

Fig. 8. Distribution of strain along the boreholes M1 and M2 due to increase of water level

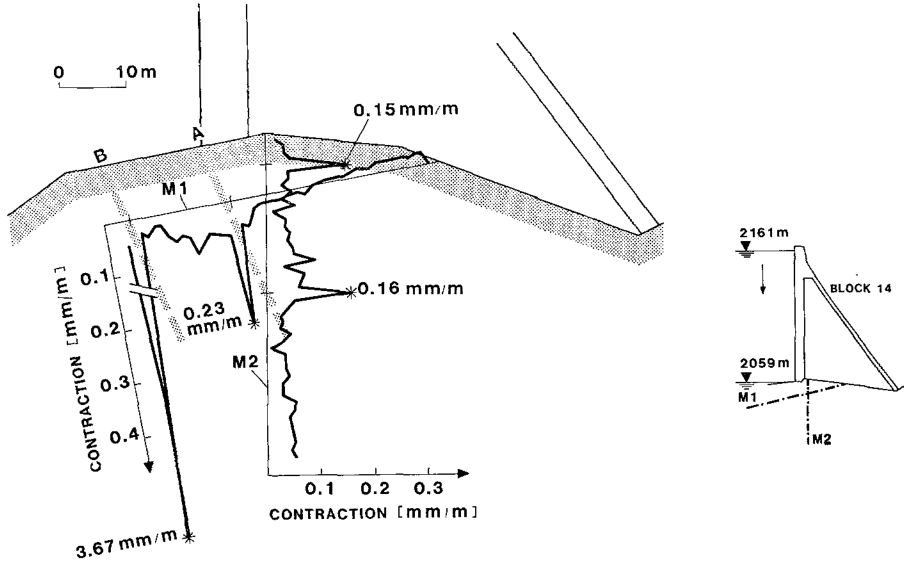

Fig. 9. Distribution of strain along the boreholes M1 and M2 due to complete fall in water level

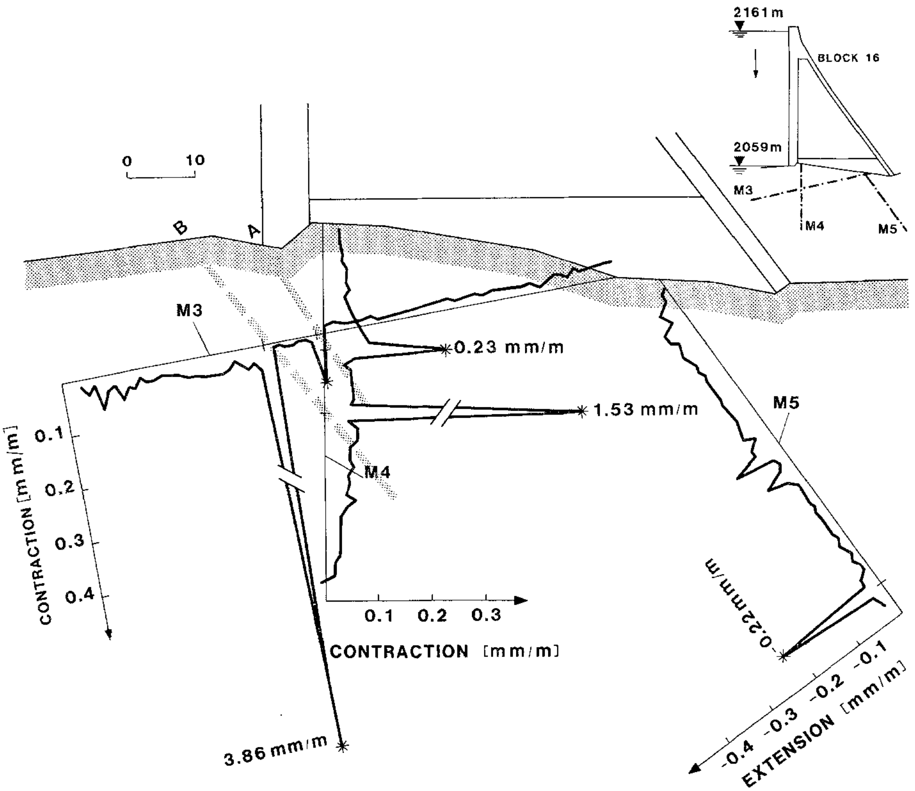

Fig. 10. Distribution of strain along the boreholes M3, M4 and M5 due to complete fall in water level

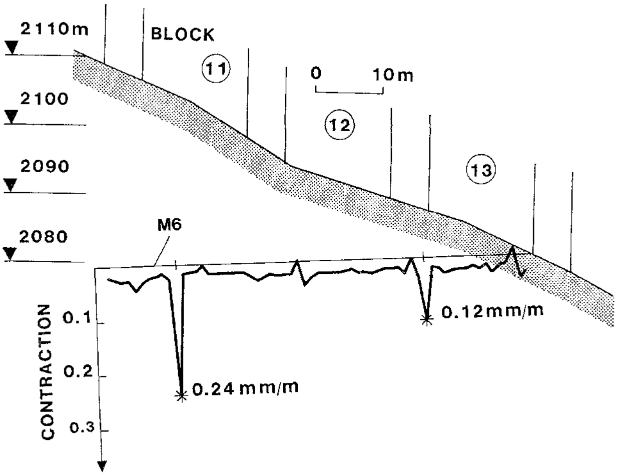

Fig. 11. Distribution of strain along the borehole M6 due to complete fall in water level

of a mud layer from the reservoir bottom adjacent to the toe of the dam, a set of longitudinal cracks on the rock surface could be observed which were obviously associated with the above-mentioned open joint B (Fig. 12).

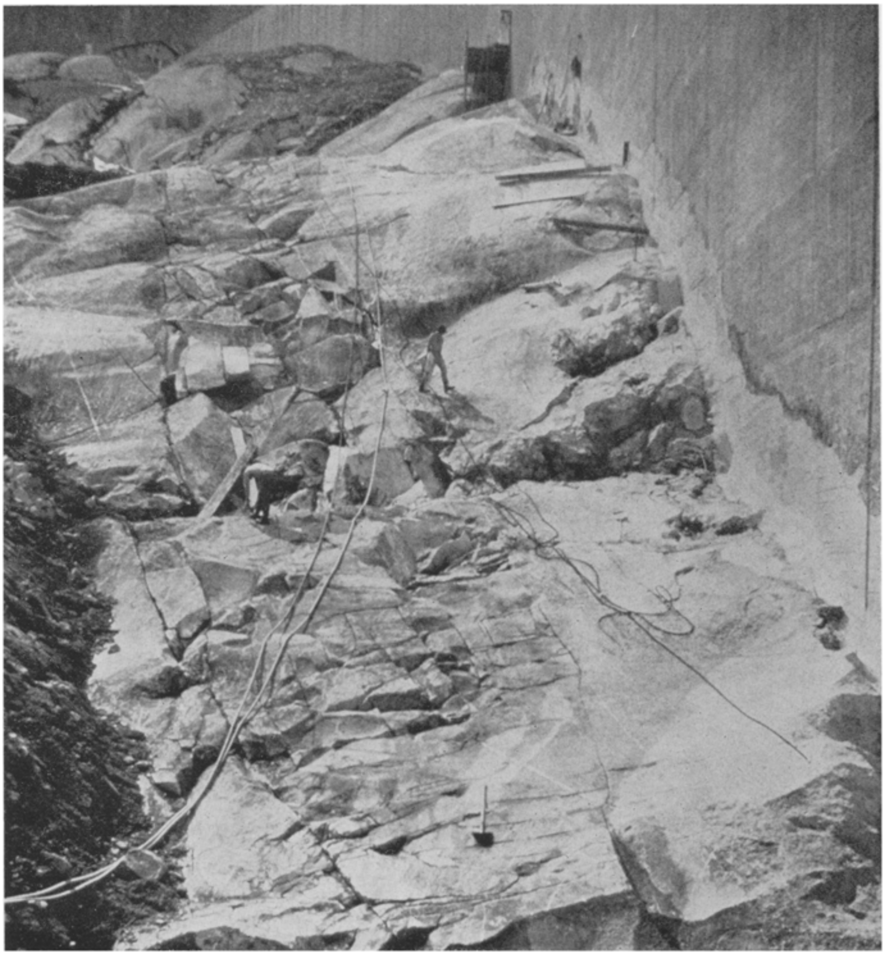

Fig. 12. Longitudinal cracks on the rock surface at the upstream toe of the dam seen after removal of mud

The question of whether only one single joint or more of them opened and closed within the 1 m base length of the measurements causing a deformation of 3.67 mm/m (Fig. 10) is of no practical relevance. Let us now consider more closely the observed strain distributions in Fig. 8. The striking feature of this figure is the great sensitivity of the strain developments to the increase of the water level at this final stage of reservoir filling. The strains brought about by the last 2 m in water level increase are about the same as the strains caused by the preceding 22 m in the filling sequence.

From the observations of the crest deflection and also from previous borehole extensometer measurements, it was noticed that large deformation of the structure starts only at a water level of approx. 2140 m. It is, therefore, not surprising to see from Fig. 9 that the emptying of the reservoir causes a complete rebound of these strains shown in Fig. 8. The three installed boreholes M3, M4 and M5 at block 16 (Fig. 10) permits a rather complete picture of the deformational behaviour of the bedrock to be obtained. Apart from the peaks, the strain distribution reveals the "normal behaviour" of the rock as well. The deformations observed in the vertical boreholes are surprisingly deep-seated. This fact, however, was also confirmed by finite element studies. The easy appraisal of the stress changes in the dam foundation due to the reservoir emptying allows the in situ Young's modulus of the rock mass to be back-calculated. Using an average strain value of 0.05 mm/m, i. e. 5×10^{-2} obtained from the borehole M4, one obtains a Young's modulus of the rock mass of $H = 30{,}000$ N/mm^2. This value only slightly differs from the one determined in the laboratory on intact rock specimens. The occurrence of only few active joints and the high rigidity of the rock mass confirmed the excellent overall rock conditions at the Albigna dam site. The strain variation along the measuring line M3 (Fig. 10) exhibits a change in sign just below the heel of the dam. The decrease in shear stresses transmitted from the dam to the rock causes compression strains upstream the dam and extension strains below the base surface. The borehole M6 (Fig. 11) was oriented in such a way that it crosses the

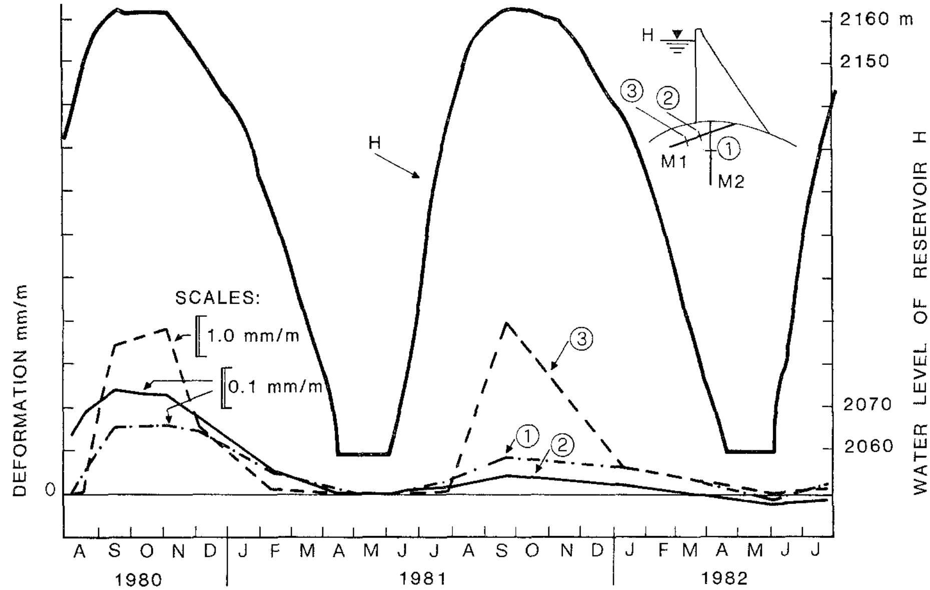

Fig. 13. Relation between reservoir water level elevation, time, and the opening of the particular joints 1, 2 and 3 at block 14

principal joint sets 1 and 2 at a steep angle. The remarkable peak in the strain distribution may be an indication for the active joint which was most probably one of the causes for the difficulties arising during the first reservoir filling in 1960.

In Fig. 13 the opening and closing of some selected active joints at block 16 are related to the reservoir water level and time. It can be seen that the first readings with the Sliding Micrometer were performed in the period August 1980 and they continued up to the end of 1982. The frequency of the readings decreased with time because later the measurements only served for control purposes. The remedial measures to stop the underseepage of the dam were also carried out in the summer of 1980. They resulted in a sharp decrease of water loss (Fig. 5). The primary purpose of the measures taken was to prevent the water from direct access to the longitudinal open joints. Therefore, a neoprene water sealing was installed reaching about 4 m high on the dam heel and extending to a maximum of 8 m on the cleaned rock surface thus forming an L shape. The width of the neoprene strip varied along the dam heel according to the distance of the B joints from the dam. The total length of this water sealing carpet amounted to 240 m, which accounted for about 60% of the crest length. To ensure a tight sealing of this extraordinary size different technological problems had to be selvod. Preliminary investigations concentrated on the question of adhesion between neoprene and concrete and neoprene and rock. The prevention of squeezing of the neoprene into open fissures acted upon by the 100 m reservoir head was a major concern. Special attention was paid to allow for large local strains in the vicinity of the active joints A and B exhibiting opening and closure.

The loss of water measured on the left bank valley side north of the block 11 could be decreased by these measures from 11 l/s to max. 1.5 l/s. The joint deformations (Fig. 13) also decreased except from the active joint B as indicated by the curve 3 which means that the water must have found its way to this joint. Fortunately, due to its sufficient distance from the heel of the dam, this joint has no influence on the underseepage of the dam. It obviously does not reach the injection curtain.

5. Conclusions

The measurement of the complete strain distribution along boreholes in the foundation rock of large dams may greatly enhance our understanding of what is going on in a jointed rock mass under load changes. In the case of the Albigna gravity dam some of the "healed" joints opened up in the course of time leading to increasing deformation of the dam and to leakage of water. By means of Sliding Micrometer measurements it was possible to clearly recognize these active discontinuities intersecting the installed boreholes. They made their presence felt by marked peak points in the strain distribution curves. Knowing the number and position of the critical discontinuities under the dam base and also their opening in function of reservoir water level, it was possible to design efficient remedial measures to halt the detrimental process in the rock mass.

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