

Innovative 3D deformometer for concrete face slab monitoring at the Saddle Dam of GERD Project

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Introduction

The Grand Ethiopian Renaissance Dam (GERD) Project is located along the Blue Nile (Abbay) in Ethiopia, a few kilometers upstream of Sudan's Roseires Dam and approximately 700 km northeast of Addis Ababa, within the Benishangul-Gumuz Region.

With an installed power of 5'150 MW and 15.7 TWh of annual energy production, the plant is one the most important projects in the Ethiopian Government's commitment to meet the country's present and future power requirements.

The whole project includes a roller compacted concrete (RCC) Main Dam (175 m high, 10.2 Mm³ of RCC volume) and a concrete faced rockfill (CFRD) Saddle Dam (65 m high, 5 km long, 15 Mm³ of embankment volume). The 5'150 MW installed power will be generated by thirteen Francis turbines in two outdoor powerhouses located at the Main Dam toe on the right and left riverside. The project also includes a six-bay gated spillway, an un-gated auxiliary spillway, an emergency spillway and two middle level outlets to allow control of the reservoir level. The Project is implemented by the Ethiopian Electric Power company (EEP), WeBuild S.p.A is the EPC contractor and Studio Pietrangeli the designer.



Fig. 1. Panoramic view of the Saddle Dam of GERDp

This paper describes the application of an innovative instrument designed to monitor the movements of the Saddle Dam's peripheral joint. Specifically, it measures the relative three-dimensional displacements of the concrete face slabs over time, relative to the inspection gallery at the dam's upstream toe.

The instrument's concept is based on the principle of the first-class lever with adjustable arms, offering both manual and automatic measurement capabilities. This device originates from an adaptation of an analog cartographic instrument, creating a triaxial pantograph equipped with electrical sensors for automatic measurement

The system offers several advantages compared to the traditional ones installed on the external surface of the slabs:

- It is fully accessible for inspection and maintenance, unlike standard 3D deformometers installed externally on the dam U/S face, which become inaccessible after backfilling and or impounding
- It is possible to suitably scale the relative displacements between slab and gallery using a simple and reliable mechanical connection, to better adapt the range of instrument movements to the expected displacements, while keeping the instrument's size compatible with physical constraints related to slab and gallery size.
- Installation is easy and fast requiring no specific design adaptations. If needed, the instrument can be installed also after impounding, by coring through the concrete peripheral joint.
- Readings can be taken both manually and using an automatic system connected to a data acquisition system (ADAS).

1. Key features of Saddle Dam of GERD Project

1.2 Project Layout

The Saddle Dam is a rockfill dam with an upstream concrete facing (CFRD). Main features are summarized hereinafter:

• Crest length	[m]	4'865
• Maximum height (H)	[m]	65
• Upstream slope	[h/v]	1.3:1
• Downstream slope	[h/v]	1.3:1
• Crest width	[m]	8
• Embankment volume	[Mm ³]	15
• Upstream face area	[m ²]	330'000

At full supply level the overall reservoir volume will be about 80'000 Mm³, 65'000 Mm³ of which will be stored above the foundation level of the Saddle Dam

The dam foundation comprises several geological units characterized by metamorphism at different grades of both volcanic, igneous and sedimentary rocks. The dam, 3.6 km long in its central portion, is founded on residual soils, while on the two banks, it is founded on rock. For the portion founded on residual soils the dam is provided with an upstream inspection gallery and plinth, and the seepage barrier is constituted by composite cut-off (i.e. the combination of plastic diaphragm and grout injections) conceived to address two different requirements: permeability correction and erosion control.

1.2 Dam zoning

The rockfill dam body includes different zones, as follows:

- Zone 1A: FINE BACKFILL
Fine-graded cohesionless silt and fine sand extended in the lower third of the dam.
- Zone 1B: COARSE BACKFILL
Random material to provide protection to zone 1A.
- Zone 2A: PERIPHERAL JOINT FILTER
Transition zone consisting of crushed rock particles up to 36 mm. In case of damage of the peripheral sealing system, the filter zone 2A will prevent the movement of silt size particles through the zone.
- Zone 2B: CUSHION
This zone provides support to the curbs and the face slab and consists of crushed sand and gravel-sized particles up to 75 mm.
- Zone 3A_1: TRANSITION 2B > 3A_2
Transition zone 6 m wide between zone 2B and zone 3A_2, consisting of selected quarry rock with maximum size of 500 mm.
- Zone 3A_2: TRANSITION 3A_1 > 3B
Transition zone between zone 3A_1 and zone 3B consisting of selected quarry rock with maximum size of 500 mm.
- Zone 3B: MAIN ROCKFILL
Quarry rock particles up to 1'000 mm.
- FILTER RESIDUAL SOIL > EMBANKMENT (2B FILTER)
A filter is foreseen above the portion of residual soil foundation between the inspection gallery and the top of the upstream trench. This filter consists of crushed sand and gravel-sized particles up to 75 mm.

- **TRANSITION RESIDUAL SOIL > EMBANKMENT**
A transition layer is foreseen above the portion of residual soil between the top of the upstream trench and the D/S toe.
- **DOWNSTREAM FACE**
Large blocks are dozed to the downstream face of the dam to protect the downstream face and to realize a toe with a gentler slope of 1.6:1 (h/v).

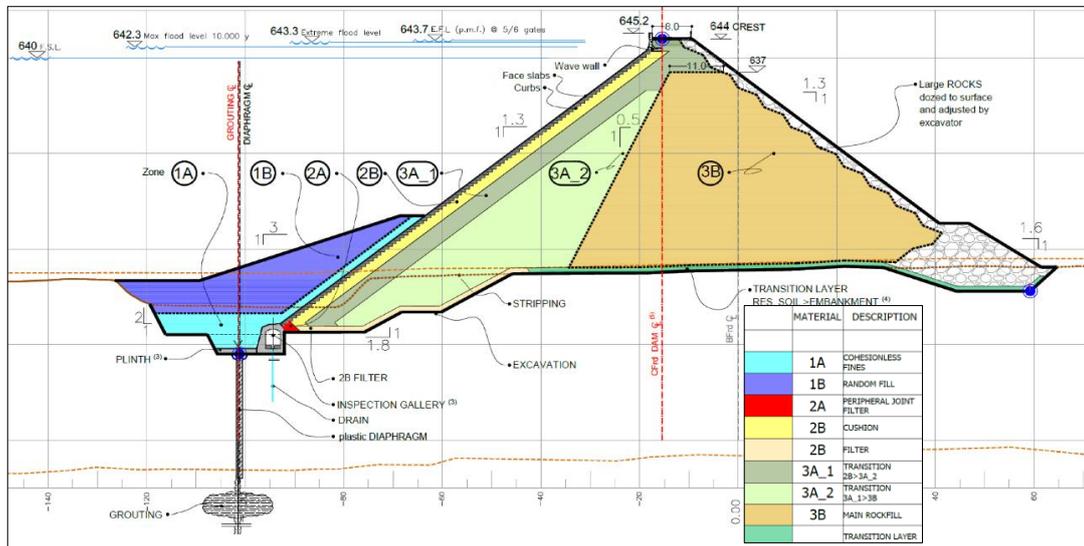


Fig. 2. Saddle Dam, Typical cross section adopted for the portion of foundation on residual soil (approx. 3600 m long)

1.2 Dam facing

The water barrier of the dam is constituted by the reinforced concrete face slabs poured on the underlying support zones, as represented schematically in Figure 3.

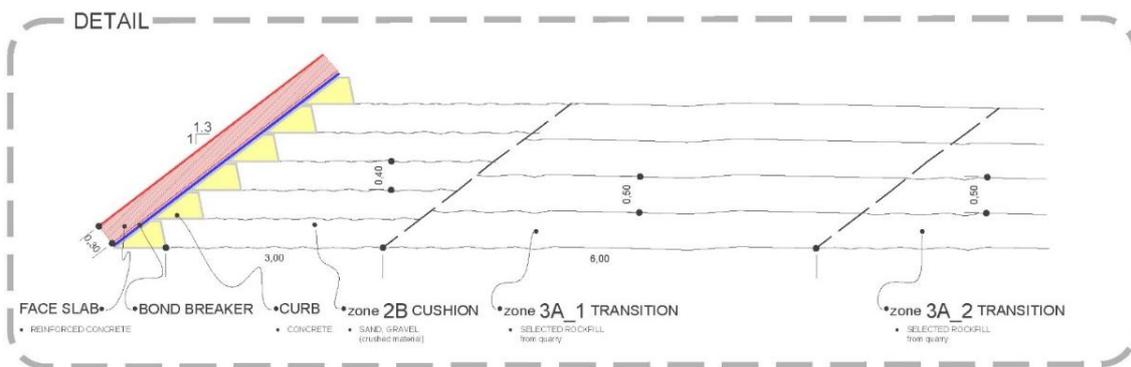


Fig.3. Saddle Dam, Zoning detail at the face slab

The dam U/S face is subdivided in about 400 concrete slabs 12.1 m wide (plus some trapezoidal “compensation” slabs with variable width to account for the polycentric shape of the dam axis). Starter slabs have been locally introduced where the slope of the plinth is such as to prevent the use of the slip-formworks from the peripheral joint.

Basic features of the reinforced concrete slabs are summarized hereafter:

- Tk [m] 0,30 Thickness of the face slab
- Wb [m] 12.1 Width of the slab
- C [-] C20D20 Concrete class
- R [-] 1-layer $\phi 16@15$ Rebars (0.45% of slab cross section area, both vertical and horizontal directions)
- c [cm] 17 Reinforcement cover

1.3 Peripheral Joint

1.3.1 Deformation analysis

Two-dimensional FEM analyses were performed to evaluate the deflection of the concrete slabs under reservoir loading due to the deformation of the underlying dam rockfill body, and to estimate the movements of the face slabs relative to the concrete plinth and inspection gallery.

Differential displacements between slab and concrete plinth / inspection gallery were calculated from the end of dam construction (i.e. when instruments are installed and initial zero-readings are taken) up to the end of reservoir filling.

For the highest dam section, calculations provided the following differential displacements at end of reservoir filling:

- ~ 1.0 cm *bridging* (i.e. opening of joint perpendicular to slab-gallery contact)
- ~ 0.5 cm *sliding* (i.e. downward movement of the slab parallel to slab-gallery contact)

The above joint movements are consistent with reference values reported in literature (ICOLD bulletin 141).

Additional analyses were carried out varying both the elastic modulus of rockfill and foundation. These analyses were done to account for the inherent variability and uncertainties of these parameters, and to study their influence on slab deflection, peripheral joint opening, and differential settlement.

Specifically, the following conservative hypotheses were analyzed:

- Rigid Foundation
Increased elastic modulus of foundation to simulate the presence of a more rigid zone intruded in the residual soil foundation (which is characterized by the several sub-vertical contacts nearly orthogonal to the dam axis)
- Rockfill compaction anomaly
Reduced elastic modulus of the rockfill to simulate a local compaction anomaly in the embankment.

Under the above conditions the joint bridging and sliding increased to 2.5 and 2.0 cm respectively.

1.3.2 Peripheral Joint System

The peripheral joint of the Saddle Dam, connecting the concrete face slabs to the plinth/gallery, comprises a double system: an internal copper waterstop and an external waterstop system.

The two systems were designed to guarantee the required watertightness while accommodating the anticipated relative movements between face slabs and plinth / gallery without being damaged and with adequate margins to cover intrinsic inaccuracies of the numerical model and possible unforeseen local weakness/defects of embankment and foundation.

The conceptual design of the external waterstop system involves two different elements with specific functions:

- Structural
The structural function (bearing of the water load over the joint opening) is performed by a mono-directional carbon-fibre layer. This material includes an 85gr/m² carbon-fibre warp yarn and an 85gr/m² fibre-glass weft yarn.
- Waterproofing
The waterproofing function is guaranteed by a 4 mm thick polyvinyl chloride plasticized geomembrane.

Both materials were supplied by MAPEI who, in coordination with Studio Pietrangeli, conducted a testing program and 1:1 scale joint prototypes in their laboratory in Milan and on-site. These prototypes allowed for the fine-tuning of the complex 3D geometry of the joint, the optimization of the shape of materials and the fastening details to the concrete structures, in particular at the crossing with vertical joints.

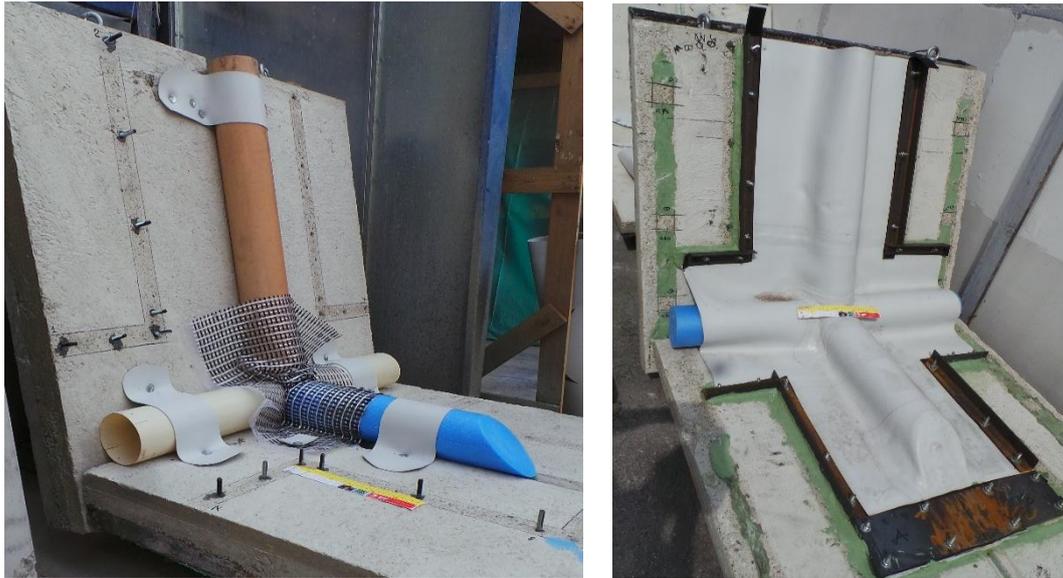


Fig.4. Prototype of the external waterstop system

2. Peripheral joint deformometers

2.1 Operating principle and key features

The standard peripheral joint monitoring system involves the application of an external three-dimensional joint meter positioned between slab and gallery/plinth joint. This setup has the inconvenience of being not accessible for maintenance, repair or replacement once the upstream backfill is placed and the reservoir is impounded.

A solution has been therefore developed to overcome this problem, allowing the measurement system to be permanently accessible also during the operating phase of the project.

To meet this requirement, the measuring system must be located inside the upstream inspection gallery. The conceptual layout of this internal measuring system is shown in the figure below.

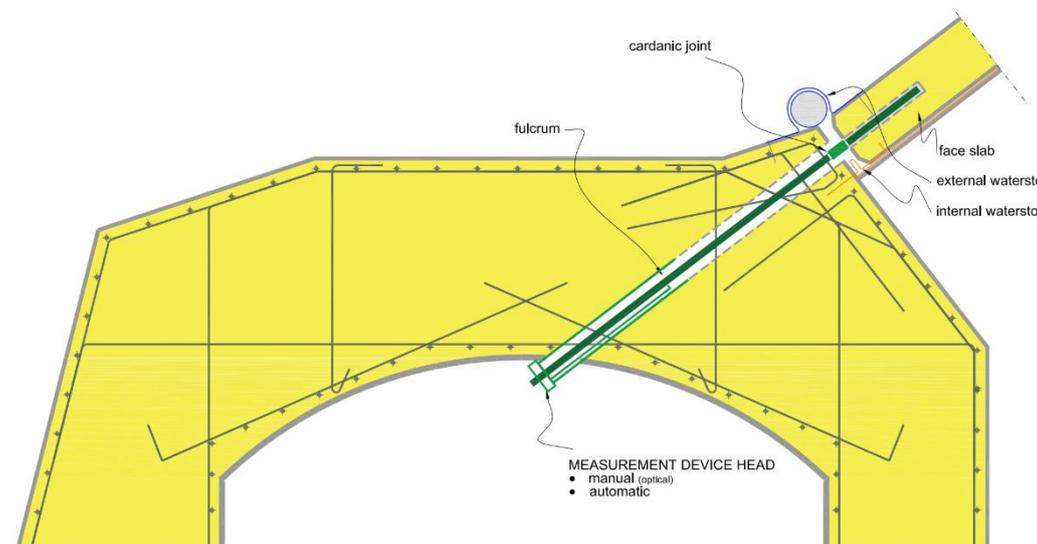


Fig.5. Conceptual scheme of internal peripheral joint deformometer

This device, developed by Pizzi Instruments in coordination with Studio Pietrangeli, consists of a lever system with a stainless-steel bar with a 20 mm diameter tubular section with one end fixed to the concrete face slab and a spherical joint close to the face slab joint, allowing the bar to rotate freely.

The tubular bar has a fulcrum at about $\frac{3}{4}$ of its length from the slab joint (this fulcrum is integral with the outer protection tube fixed to the gallery ceiling), forming a Class I lever with a 3 to 1 arm ratio. Slab movements are

thus transferred to the head of the instrument, within the inspection gallery, reduced by one-third of their actual value. The leverage ratio can be adjusted, depending on the anticipated relative movements between gallery and slab, by acting on the support and adjustment bars of the instrument.

The terminal part of the tubular bar houses a transmission rod that extends into the instrument, acting as a "witness" to the movements being measured. This rod also forms the rack for measuring movement along the "Z" axis.

The instrument is made watertight by a stainless-steel cover and a silicone rubber bellows that seal the bar's entry point.

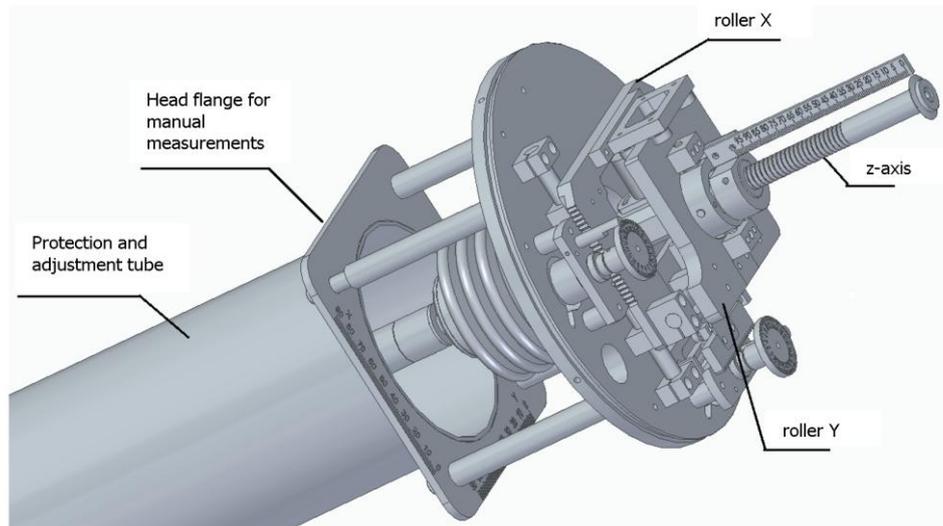


Fig.6. Detail of instrument's head (inspection gallery side)

The measurement system is primarily mechanical, but it can be equipped with three potentiometric transducers for automated readings. Manual or optical readings are always possible using the three scales placed on the chassis.

The tubular rod is attached to the slab using a centering device. This device is fixed into a pre-drilled hole and features a threaded connector and gaskets. The annular space between the threaded connector and the drilled hole is injected to ensure adequate coupling between the connector and the slab.

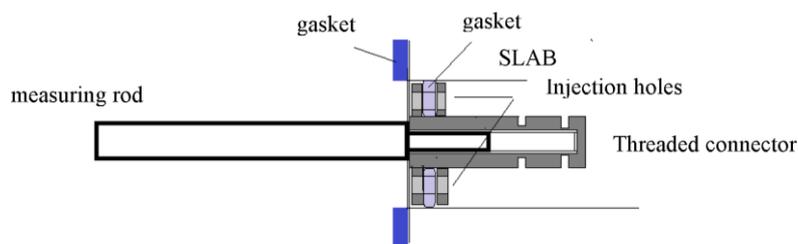


Fig.7. Face slab anchoring detail

It is important to note that any movement along the Z-axis will proportionally modify the original leverage ratio. This modification must be accounted for when evaluating the X and Y movements.

The conceptual design of this instrument is rooted in the old-fashioned cartographic restitution instruments that used levers and translator system to draw 3D profiles. In stereoscopic photo-restitutions techniques two images, taken by cameras with the same orientation and at a predetermined distance, were placed on a reference plane and then, by means of an optical system constrained to movable rollers (that could move with respect to each other in the three orthogonal directions) different points of the images were collimated. The coordinates of the collimated point were then determined from the resulting positions assumed by the two carriages.

2.2 Instrument installation

No. 48 instruments were installed after the completion of the inspection gallery and face slab. This installation required precisely drilling holes through the inspection gallery ceiling and the face slab.

It is worth noting that incorporating suitable supports and sleeve pipes into the concrete element during casting would eliminate the need for any drilling or coring operation.

The following pictures show the setup of the lightweight drilling machine positioned on scaffolding for the drilling operations. The portion of the drill crossing the inspection gallery ceiling up to the joint has a 152 mm diameter, while the portion extending into the concrete face slab was 72 mm. The PVC pipe visible next to the head of the steel tube on the bottom right of the picture below is aimed at draining any water present within the peripheral joint (between the external and internal waterstops), thereby protecting the instruments from dripping.



Fig.8. Installation of 3D instrument inside dam gallery (left) and detail of manual measurement on tube's head (right top)

2.3 Analysis of readings

Initially, after the placement of upstream backfill, differential movements between slabs and inspection gallery / plinth have been monitored using conventional external three-dimensional deformometers, at first. Each of these external deformometers consists of three vibrating wire extensometers installed on a support / leverage system across the joint, allowing the monitoring of the joint movements in the three directions (bridging, sliding and left-right).

After the installation this system was protected against the upstream toe backfill with a steel casing and wrapped with a geotextile.

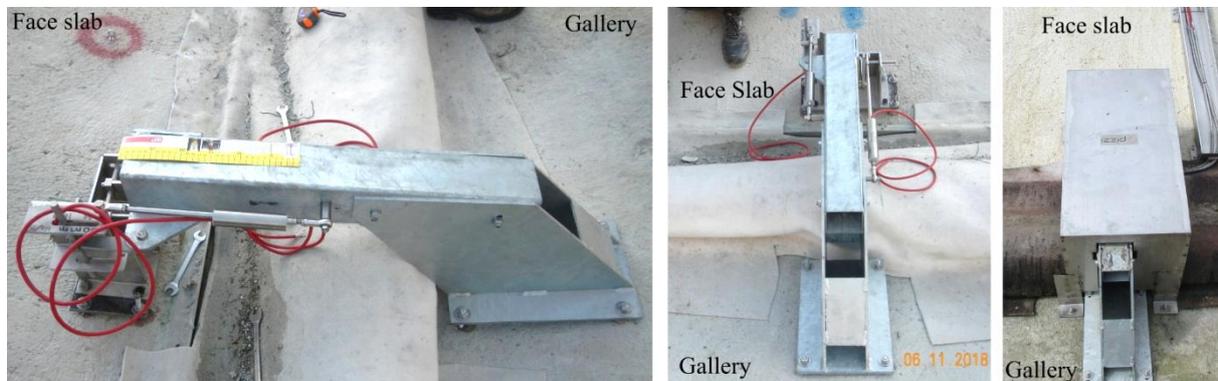


Fig. 9. External 3D peripheral joint deformometer, during installation (left & center) and with protective steel casing (right)

Soon after the placing of the backfill, some external deformometers exhibited anomalous behavior, inconsistent with the effect of backfill load.

Some of the instruments were inspected by locally removing the backfill material. The investigations showed that, in some cases, the protective casings were excessively deformed under the backfill load, causing the casings to touch the leverage system, leading to “apparent” differential displacements.



Fig. 10. Local removal of backfill to allow the inspection of the external deformometers

After this inspection, and in consideration of the large earth-moving activities that would have been required to replace all the damaged casings protecting the external deformometers, it was decided to develop the alternative internal deformometers described in the previous paragraph. The Contractor decided, as a precaution, to install the alternative internal instrument in correspondence of all the external instruments installed under the backfill, even though some of them were still working properly. The possibility of getting readings from the same location with two different instruments was then used for cross-check.

The following figures compare the measurements from an external deformometer with those acquired by the innovative internal system during reservoir impounding. It is observed that measurements remained congruent after the backfill is replaced over the slabs and the reservoir is impounded up to 30 meters above the instrument's elevation.

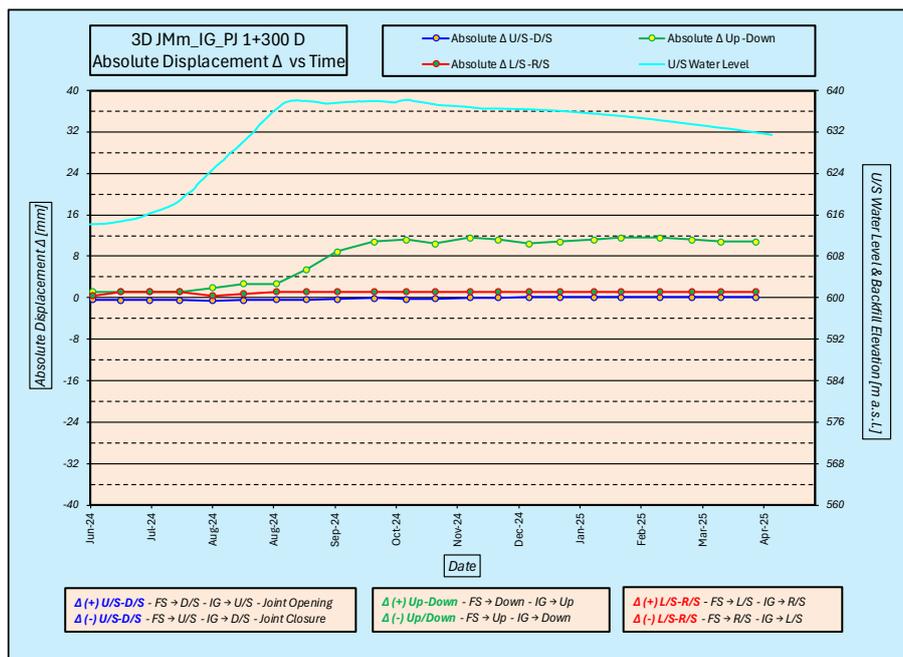


Fig. 11. Internal deformometer readings at ch. 1+300D

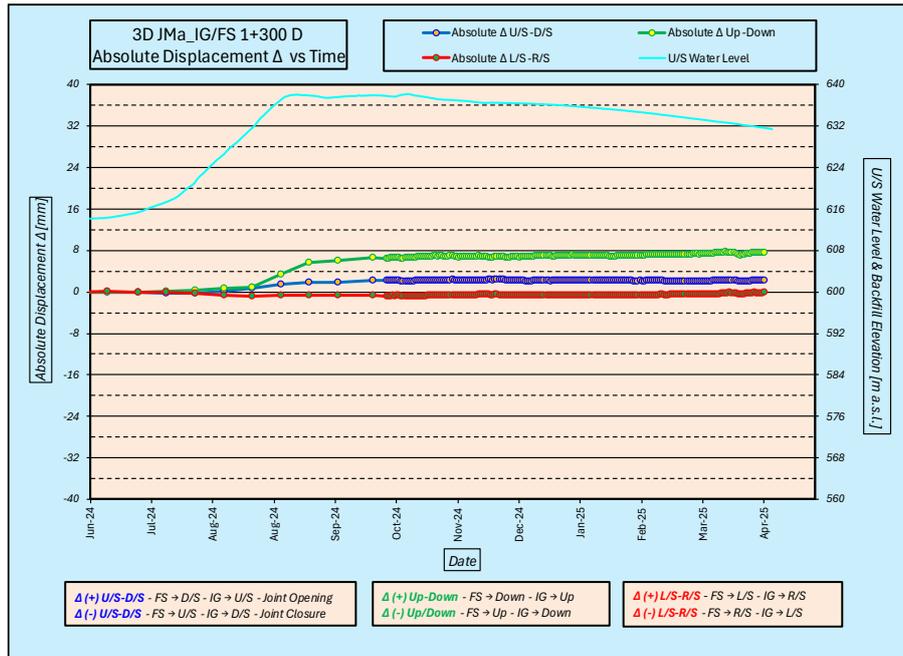


Fig. 12. External Deformometer readings at ch. 1+300D

The measurements are very close to each other, with a similar trend and differences between homologous sensors in the range of 1-3 mm.

5. Conclusions

This paper has described the application of an innovative instrument designed to monitor the relative three-dimensional displacements between the concrete face slabs and the inspection gallery at the upstream toe of the Concrete Faced Saddle Dam of Grand Ethiopian Renaissance Dam (GERD) Project's.

The concept of the instrument is based on the principle of the first-class lever with adjustable arms offering both manual and automatic measurement capabilities. The measurement device is originated from an adaptation of the analogue cartographic instrument, creating a triaxial pantograph equipped with electrical sensors for automatic measurement.

No. 48 innovative 3D deformometers have been successfully installed and are under monitoring with almost the full impounding of the GERD project. The behavior of this instrument has been fully validated by comparing its readings with those from the standard external instrument.

This innovative instrument offers several advantages compared to conventional external systems:

- It remains always accessible for inspection and maintenance throughout the operating life of the project whereas the external ones become practically inaccessible after backfilling and or impounding.
- It can be easily installed during gallery construction and slab concrete placement by simply incorporating suitable supports and sleeve pipes into the concrete element during casting, eliminating the need for any coring operations.
- In case of needs, it is possible to replace or install additional instruments during the operation of the project (for instance in specific zone showing anomalous behaviour and/or not previously instrumented) without requiring reservoir levels to be lowered.
The installation, performed by coring, is fast requiring only 3-4 days of work.
- Readings can always be taken both manually and using an automatic system connected to a data acquisition system (ADAS).
- It is possible to suitably scale the relative displacements between slab and gallery using a simple and reliable mechanical connection, to better adapt the range of instrument movements to the expected displacements, while keeping the instrument's size compatible with physical constraints related to slab and gallery size.

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F. Pizzi, is the founder and administrator of Pizzi Instruments Srl, a company that designs and produces precision instruments for the control of dams and large structures in general. He began to deal with monitoring at Officine Galileo in Florence in 1977. In 1982 he started this activity on his own, directly following both the design and production of both mechanical and electronic instruments. He also designs and produces non-standard instruments based on specific problems and/or needs.